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# THESIS

**A HUMAN-AUTOMATION INTERFACE MODEL TO GUIDE AUTOMATION DESIGN OF SYSTEM FUNCTIONS: A WAY TO ACHIEVE MANNING GOALS IN NEW SYSTEMS**

by

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December 2005

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A major component of the US Army's Future Combat Systems (FCS) will be a fleet of eight different manned ground vehicles (MGV). There are promises that 'advanced automation' will take on many of the tasks formerly performed by soldiers in legacy vehicle systems. However, the current approach to automation design does not relieve the soldier-operator of tasks; rather, it changes the role of the soldiers and the work they must do, often in ways unintended and unanticipated. This thesis proposes a coherent, top-down, overarching approach to the design of a human-automation interaction model. First, a qualitative model is proposed to drive the functional architecture and human-automation interface scheme on the MGV fleet. Second, proposed model is applied to a portion of the functional flow of the common crew station on the MGV fleet. Finally, the proposed model is demonstrated quantitatively via a computational task-network modeling program. The modeling approach offers insights into the impacts on human task-loading, workload, and human performance. Implications for other domains in human systems integration are discussed. The proposed model gives engineers and scientists a top-down approach to explicitly define and design the interactions between proposed automation schemes and the human crew.

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# A HUMAN-AUTOMATION INTERFACE MODEL TO GUIDE AUTOMATION OF SYSTEM FUNCTIONS: A WAY TO ACHIEVE MANNING GOALS IN NEW SYSTEMS

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# ABSTRACT

A major component of the US Army's Future Combat Systems (FCS) will be a fleet of eight different manned ground vehicles (MGV). There are promises that 'advanced automation' will take on many of the tasks formerly performed by soldiers in legacy vehicle systems. However, the current approach to automation design does not relieve the soldier-operator of tasks; rather, it changes the role of the soldiers and the work they must do, often in ways unintended and unanticipated. This thesis proposes a coherent, top-down, overarching approach to the design of a human-automation interaction model. First, a qualitative model is proposed to drive the functional architecture and human-automation interface scheme on the MGV fleet. Second, proposed model is applied to a portion of the functional flow of the common crew station on the MGV fleet. Finally, the proposed model is demonstrated quantitatively via a computational task-network modeling program. The modeling approach offers insights into the impacts on human task-loading, workload, and human performance. Implications for other domains in human systems integration are discussed. The proposed model gives engineers and scientists a top-down approach to explicitly define and design the interactions between proposed automation schemes and the human crew.

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# TABLE OF CONTENTS

## LIST OF FIGURES

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# LIST OF TABLES

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACM | Association for Computing Machinery |
| AFM | Autonomous Flight Management |
| AGS | Armored Gun System |
| ANSI | American National Standards Institute |
| APA | American Psychological Association |
| ARL | Army Research Lab |
| ARV | Armed Robotic Vehicle |
| ASCM | Anti Ship Cruise Missile |
| ASD | Air Self Defense |
| ASW | Anti Submarine Warfare |
| ATD | Advanced Technology Demonstration |
| B.S | Bachelor of Science |
| BA | Basic Access |
| BAE-SC | BAE – Santa Clara |
| C2V | Command and Control Vehicle |
| CA | Crewman's Associate |
| CA-ATD | Crewman's Associate – Advanced Technology Demonstration |
| CCS | Common Crew Station |
| CFM | Common Function Model |
| CIWS | Close in Weapons System |
| COA | Course of Action |
| COP | Common Operational Picture |
| CRADA | Cooperative Research and Development Agreement |
| CSG | Carrier Strike Group |
| CSRDF | Crew Station Research and Development Facility |
| CTP | Common Tactical Picture |
| DC | Data Collection |
| DoD | Department of Defense |
| DoDI | DoD Instruction |
| DT | Developmental Testing |
| DTIC | Defense Technical Information Center |
| ESG | Expeditionary Strike Group |
| EW | Electronic Warfare |
| FA | Function Allocation |
| FA/TA | Function Analysis / Task Analysis |
| FCS | Future Combat Systems |
| FM | Field Manual (Army) |
| FoS | Family of Systems |
| FRMV | FCS Recovery and Maintenance Vehicle |
| GDLS | General Dynamics Land Systems |
| HFE | Human Factors Engineering |
| HFETAG | Human Factors Engineering Technical Advisory Group |

| | |
|---|---|
| HRED | Human Research and Engineering Directorate |
| HSI | Human Systems Integration |
| ICV | Infantry Carrier Vehicle |
| IEEE | Institute of Electrical and Electronic Engineers |
| IMPRINT | Improved Performance Research and Integration |
| IMS | Intelligent Munitions System |
| IPT | Integrated Products Teams |
| IRD | Interim Requirements Document |
| IT | Information Technology |
| KPP | Key Performance Parameter |
| LCDR | Lieutenant Commander |
| LCS | Littoral Combat Ship |
| LHX | Light Helicopter Experimental |
| LOA | Levels of Automation |
| LSI | Lead Systems Integrator |
| MABA-MABA | Men Are Better At – Machines Are Better At |
| MAI | Manning Affordability Initiative |
| MANPRINT | Manpower and Personnel Integration |
| MCR | Main Control Room |
| MCS | Mounted Combat System |
| MDMP | Military Decision Making Process |
| MGV | Manned Ground Vehicles |
| MIW | Mine Warfare |
| MOS | Military Occupational Specialties |
| MPT | Manpower Personnel and Training |
| MULE | Multifunctional Utility Logistics and Equipment |
| MV | Medical Vehicle |
| MWL | Mental Workload |
| NASA | National Aviation and Space Administration's |
| NATO | North Atlantic Treaty Organization |
| NLOS | Non Line of Sight |
| NPS | Naval Postgraduate School |
| NSN | National Stock Number |
| O&O | Operational & Organizational (Plan) |
| OE | Operational Environment |
| OMB | Office of Management and Budget |
| ONR | Office of Naval Research |
| OODA | Observe Orient Decide Act |
| ORD | Operational Requirements Documents |
| OT | Operational Testing |
| PCD | Procurement Control Drawing |
| PEO | Program Executive Officer |
| PIDS | Prime Item Development Specifications |
| R&D | Research and Development |
| RD&E | Research, Development, and Engineering |

| | |
|---|---|
| RSV | Reconnaissance and Surveillance Vehicle |
| S&T | Science and Technology |
| SA | Situation Awareness |
| SE | Systems Engineering |
| SI | Systems Integration |
| SITREP | Situation Report |
| SMART | Self-Monitoring Analysis and Reporting Technology |
| SME | Subject Matter Experts |
| SoS | System of Systems |
| SPSS | Statistical Package for the Social Sciences |
| SUGV | Small Unmanned Ground Vehicle |
| SUW | Surface Warfare |
| TA | Task Analysis |
| TACOM | Tank Automotive Command (US Army) |
| TAD | Target Audience Description |
| TADSS | Training Aids Devices Simulators and Simulations |
| TARDEC | TACOM Research, Development, and Engineering Center |
| TDFA | Top Down Function Analysis |
| TDRA | Top Down Requirements Analysis |
| TN | Technical Note |
| TRADOC | Training and Doctrine Command (US Army) |
| TTP | Tactics Techniques and Procedures |
| UA | Unit of Action |
| UAMBL | Unit of Action Maneuver Battle Lab |
| UAV | Unmanned Aerial Vehicles |
| UDLP | United Defense Limited Partnership |
| UE | Unit of Employment |
| UGS | Unattended Ground Sensors |
| USN | US Navy |
| V.I. | Vehicle Integrators |
| WMI | Warfighter Machine Interface |
| WSRT | Wilcoxon Signed Ranks Test |

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# EXECUTIVE SUMMARY


A major component of the US Army's Future Combat Systems (FCS) will be a fleet of eight different manned ground vehicles (MGV). There are promises that 'advanced automation' will accomplish many of the tasks formerly performed by soldiers in legacy vehicle systems. However, the current approach to automation design does not relieve the soldier-operator of tasks; rather, it changes the role of the soldiers and the work they must do, often in ways unintended and unanticipated. This thesis proposes a coherent, top-down, overarching approach to the design of a human-automation interaction model.

Given the available literature on design of automation and the need at BAE Systems (one of the defense contractors building the MGV fleet), a qualitative model is proposed to drive the functional architecture and the human-automation interface scheme on the MGV fleet. The model starts with a five-stage model of information processing for the human-automation interaction scheme in the FCS MGV fleet (Table 1). It stands squarely on the shoulders of a few giants in the field of human factors and automation research and development (Parasuraman, Sheridan, Wickens, 2000; Kaber & Endsley, 2004).

Table 1. Five-Stage Model of Information-Processing for Human-Automation Interaction Scheme in the FCS MGV Fleet

| ***Stage*** | | ***Definition*** |
|---|---|---|
| **1** | **Information Acquisition** | Acquisition and registration of multiple sources of information. Positioning and orienting of sensory receptors, sensory processing, initial pre-processing of data prior to full processing, and selective attention |
| **2** | **Information Analysis** | Conscious perception and manipulation of processed and retrieved information in working memory. Also includes cognitive operations (rehearsal, integration, and inference) occurring prior to point of decisions. |
| **3** | **COA Development** | Generating (a) the decisions that need to be made, followed by (b) formulating options or task strategies for achieving goals. |

| Stage | | Definition |
|---|---|---|
| 4 | **Decision Selection** | Selection of a particular option, course of action (COA), or strategy to carry out. Decision(s) are reached based on the Analysis stage (cognitive processing), the COA Development stage, and expertise (human or software). |
| 5 | **Action Implementation** | Consistent with the decision selection(s), carrying out the chosen option, COA, or strategy, whether through control actions at an interface or other means. |

The proposed human-automation interface model is shown graphically in Figure 1. This demonstrates the five stages of information processing, as well as the possibility for ten levels of automation (LOA) within each of the five stages. It retains the intuitiveness of the original model from Parasuraman et al. (2000) while allowing system engineers and designers to explicitly define how the human and proposed automation will interact so we might be able to understand how the two will perform as part of the overall system in development. Functions A/A′ and Systems B/B′ will be provided as examples of how a human-automation interaction scheme might be designed conceptually.

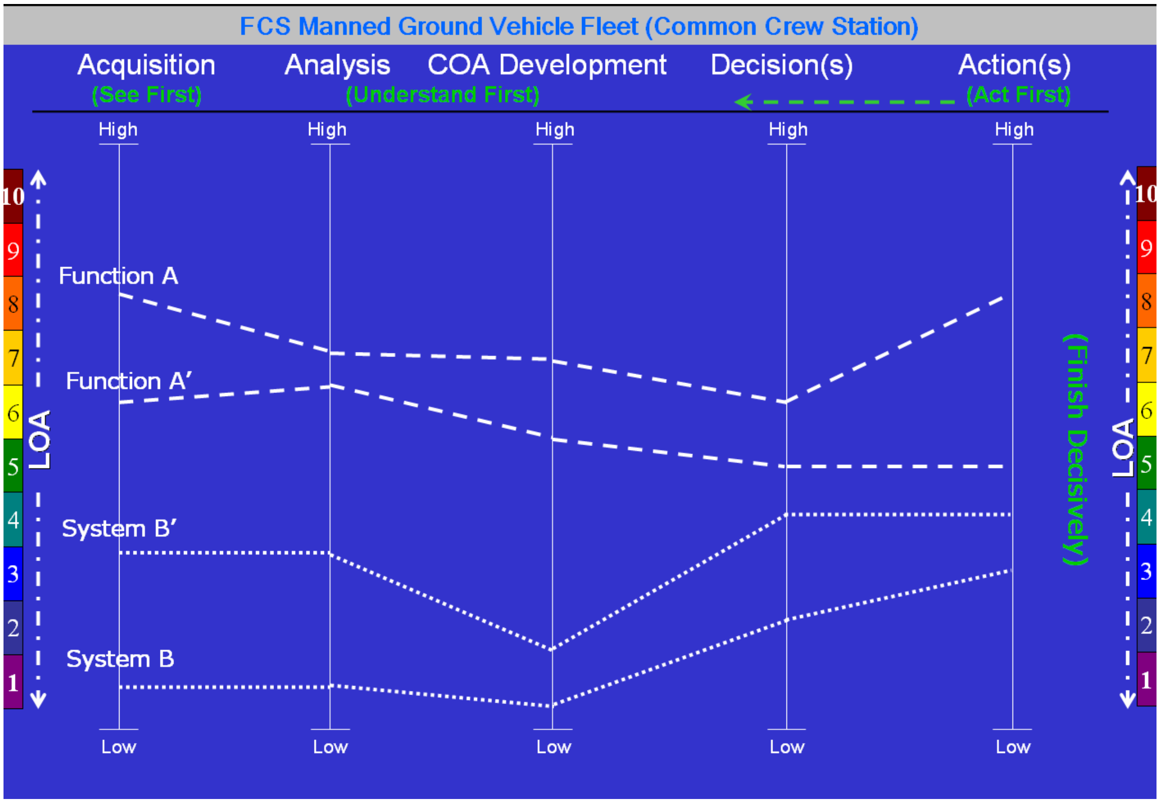


Figure 1. Qualitative Model for Design for Human-Automation Interaction in the FCS MGV Fleet. Note how the UA 'Quality of Firsts' are related to the proposed model.

Therefore, to further the ideals of this thesis, Figure 2 graphically presents two possible human-automation interface schemes to achieve the common function of Local Defense. The current scheme (yellow line on the graph) employs almost no automation, only giving the vehicle commander some physical aids to allow arming and firing of the chosen weapon with a single button press. The vehicle commander is totally responsible for detecting, identifying, and tracking any local threats. In the Engagement stage, the commander must then make a series of decisions (probably in rapid order) that starts with whether to engage the target or not, followed by selections of the appropriate weapon and ammunition. At the Shoot/Report stage, automation design gives the commander some physical help by only requiring a simple button press to arm the chosen weapon, and then another single-button press to fire the weapon. Preparation and transmission of the digital (i.e., typed text) situation report is left completely with the commander.

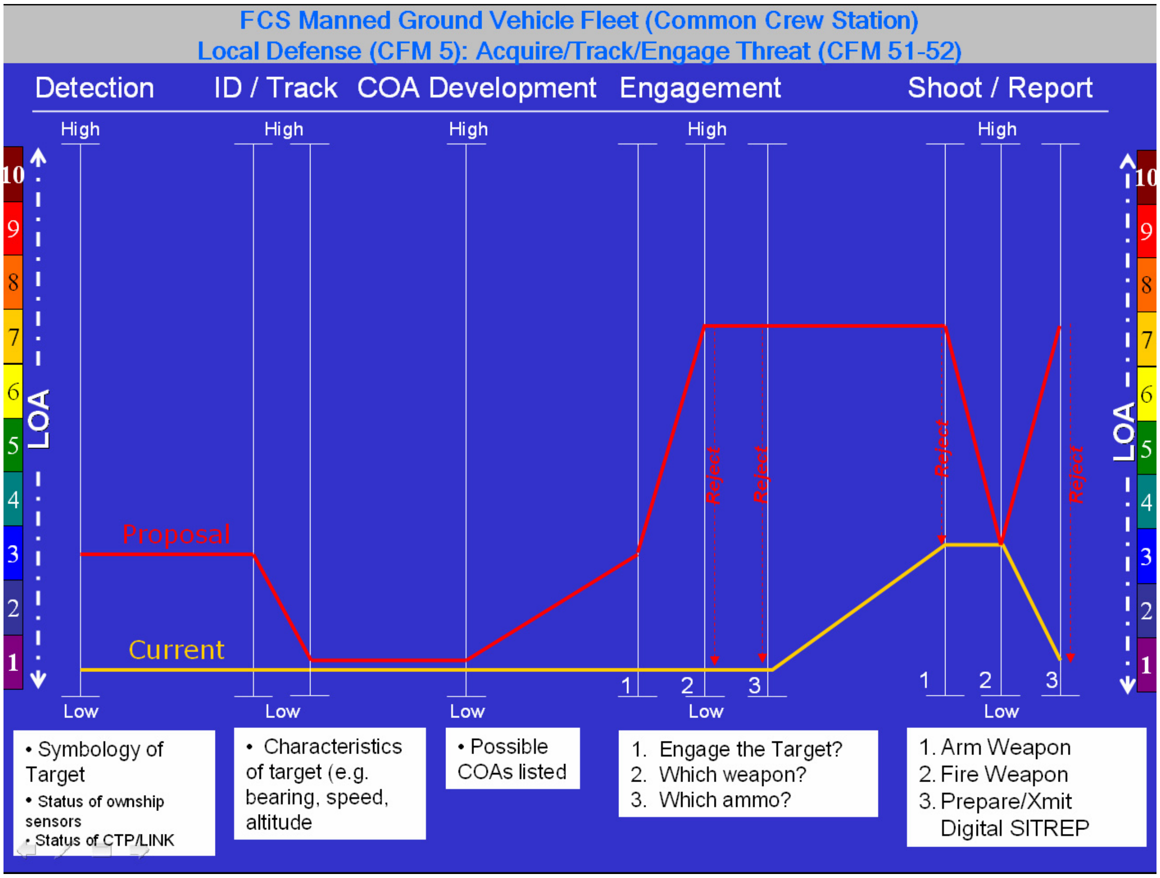


Figure 2. Qualitative Model Applied to the Local Defense Function

This thesis implemented the qualitative model applied to the MGV via a computational analysis using task-network modeling and Monte Carlo simulation from a software package called IMPRINT, developed by the US Army Research Lab's Human Research and Engineering Directorate. Using the proposed architecture in Figure 2, the Local Defense function of the MGV fleet was modified to reflect the new and resulting human-automation architecture by 'dialing in' selected levels of automation for selected tasks.

Comparison of operator task-loading of the current systems vs. the proposed automation architecture shows that it is possible to reduce operator task-loading. A primary conclusion of the thesis is that by applying the proposed human-automation interface model to other functions in the vehicles, it is possible to make further reductions in operator task-loading and mental workload. This will also support attempts to achieve

the current ORD requirement for a vehicle operable by a 2-soldier crew.  This work is intended to contribute to the effort to ensure that vehicle systems in the MGV fleet can accomplish the overall unit mission and the FCS' mission as an acquisition program. Even if we eventually conclude that an additional crewmember is required on the various MGV vehicles, the same qualitative and quantitative models can be used to gain a clear understanding of the human-automation interaction as well as the some of the human performance ramifications in terms of mental workload.

With this tool in hand, the exact role of the Soldier operators as the central component of the vehicle systems is clearly understood well before the fielding of the vehicle systems.  This is but *one way* (among several) to work toward the ORD requirement for a 2-soldier crew.  But, even if the 2-soldier crew requirement is relaxed, a coherent plan for automation will help to ensure soldier performance and system effectiveness. The focus of the model is to ensure that a reduced-crew can perform *well enough* (not optimally) to accomplish all of the functions and tasks asked of the total vehicle system.

The models and techniques proposed in this thesis have implications beyond just the FCS manned vehicle.  The general model and analytical processes, or similar approaches, are certainly necessary in a slew of complex systems that lack an 'automation philosophy' to guide the design of a proper interaction between human and automation to ensure total system performance.

# I. INTRODUCTION AND BACKGROUND

## A. THE U.S. ARMY'S FUTURE COMBAT SYSTEMS (FCS) AND THE PROMISE OF AUTOMATION

Future Combat Systems (FCS) is a joint, networked system of systems made up of 18 individual systems, the network, and most importantly, the Soldier. FCS will be connected via an advanced network architecture that will enable levels of joint connectivity, situational awareness and understanding, and synchronized operations heretofore unachievable. FCS will operate as a System of Systems (SoS) that will network existing systems, systems already under development, and systems to be developed to meet the requirements of the Army's Future Force Unit of Action (UA).

FCS comprises 18+1+1 systems consisting of unattended ground sensors (UGS); two unattended munitions, the Non-Line of Sight – Launch System (NLOS-LS) and Intelligent Munitions System (IMS); four classes of unmanned aerial vehicles (UAVs) organic to platoon, company, battalion and Unit of Action (UA) echelons; three classes of unmanned ground vehicles, the Armed Robotic Vehicle (ARV), Small Unmanned Ground Vehicle (SUGV), and Multifunctional Utility/Logistics and Equipment Vehicle (MULE); and the eight manned ground vehicles (18 individual systems); plus the network (18+1); plus the Soldier (18+1+1) (US Army, 2005).

BAE Systems (formerly United Defense, Limited Partnership [UDLP]) and General Dynamics Land Systems (GDLS) have been named the Vehicle Integrators (V.I.) for the manned ground vehicle (MGV) fleet of FCS. The V.I. team of BAE Systems and GDLS are jointly responsible for design, development, and production of the MGV fleet. The eight vehicles in the MGV fleet are: Mounted combat system (MCS), Infantry carrier vehicle (ICV), Non-line-of-sight cannon (NLOS-C), Non-line-of-sight mortar (NLOS-M), Reconnaissance and surveillance vehicle (RSV), Command and control vehicle (C2V), Medical vehicle (treatment and evacuation variants; MV-E and MV-T), and the FCS Recovery and Maintenance Vehicle (FRMV). Operating under a cooperative research and development agreement (CRADA) between the Naval Postgraduate School

(NPS) and BAE's offices in Santa Clara, CA (BAE-SC), engineers at BAE have partnered with NPS to investigate human systems integration (HSI) issues related to the MGV fleet.

BAE Systems is responsible for development and manufacture of several vehicles in the MGV fleet, as well as design of the common crew station (CCS) between all of the MGV fleet. The FCS Operational Requirements Documents (ORD; dated 31 January 2005), requires that all FCS Manned Systems must be operable by a 2-man crew (a driver and vehicle commander), with the rationale being that the platform must be simple enough for a 2-man crew to operate effectively (US Army, 2005, p. D-7). The lone exception is the MCS, a tank-like vehicle which will have a three-person crew. The limit of two soldiers is an intense effort by the Army to gain significant life-cycle cost savings by eliminating costly manpower. Current armored vehicles in the Army fleet typically have at least 3-4 soldiers in the crew, sometimes more for certain artillery vehicles.

Early design meetings for the FCS' Warfighter-Machine Interface (WMI) have routinely promised that 'advanced automation' will assume many of the tasks formerly performed by soldiers in legacy vehicle systems. However, there does not appear to be a coherent plan to design the human-automation interface. Instead, various engineers have proposed a bottom-up process for automation, starting with a detailed task analysis for the common crew station. (personal communications, Jeffrey Powers, Dr. Patty Lakinsmith, Dr. Douglas Neil, [of BAE Systems], June 2005). Then the V.I. team will decide what tasks to automate based on technical feasibility, without regard to the overall human-automation interface scheme that would result. There are many talented, dedicated engineers and scientists working hard to generate ideas and designs for automation on the MGV fleet, but without any general philosophy or overarching design concept for automation.

The overall ideas being proposed for a human-automation scheme are inappropriate based on past experience and lessons learned, literature reviews, and multiple transportation accidents (aircraft, cars, and trains). No coherent guide exists tot guide decision about what types or and how much automation. Without a reasoned plan for the functional architecture of automation design, any automation pieces added to a

complex system are not likely to relieve a human operator of tasks; it will merely shifts them from being manual tasks to more supervisory ones. Thus, the human operator must become a 'super-supervisor' in order to monitor and understand everything that is being automated. The MANPRINT/Human Factors chief at BAE confirms that the V.I. would benefit from an overarching guide to design the human-automation interface scheme across the MGV.

Therefore, operating within a cooperative research and development agreement (CRADA) between NPS and BAE-SC, the goal of this thesis was to provide a process for developing a top-down, overarching approach to explicitly define and design the interaction between proposed automation schemes and the human crew. It shows an approach to developing a functional architecture between human and automation for the total system. While it was developed for engineers and scientists at BAE and the V.I., the process can be expanded to a wide array of domains (aviation, space, maritime, ground transportation, manufacturing, etc.). It can be applied to the FCS MGV fleet to reduce operator workload and possibly improve crew performance. There are implications for crew size in the total vehicle system.

## B. EXAMPLES OF HUMAN FAILURES DUE TO POOR AUTOMATION DESIGN

There is a sizable research base examining human capabilities (and subsequently, human error and failure) involved in work with automated systems. New technologies applied to the control of complex person-machine systems can have a significant impact on operator performance and training requirements. While reviewing US Army air defense command and control, Hawley, Mares, and Giammanco (2005, p. 3) noted that "the crux of the problem of new technologies applied to system control is that they tend to remove human operators from moment-to-moment, on-line control and relegate them to the role of supervisory controllers. A variety of research has indicated that the consequences of this change are not always positive" (Hawley, Mares, & Giammanco, 2005).

Norman (1990) detailed the case of a fuel leak in a commercial airliner in which a vigilant second officer detected the signs of one possible problem, but failed to detect another. Here is a quote from the accident report, as reported in Norman's paper (p. 6):

> Shortly after level off at 35,000 ft... the second officer brought to my attention that he was feeding fuel to all 3 engines from the number 2 tank, but was showing a drop in the number 3 tank. I sent the second officer to the cabin to check that side from the window. While he was gone, I noticed that the wheel was cocked to the right and told the first officer who was flying the plane to take the autopilot off and check. When the autopilot was disengaged, the aircraft showed a roll tendency confirming that we actually had an out of balance condition. The second officer returned and said we were losing a large amount of fuel with a swirl pattern of fuel running about mid-wing to the tip, as well as a vapor pattern covering the entire portion of the wing from mid-wing to the fuselage. At this point we were about 2000 lbs. out of balance....

In this example, the second officer (flight engineer) provided valuable feedback that something seemed wrong with the fuel balance. "The automatic pilot had quietly and efficiently compensated for the resulting weight imbalance, and had the second officer not noted the fuel discrepancy, the situation would not have been noted until much later, perhaps too late (1990, p. 6). Norman argued that "it is essential to examine the entire system: the equipment, the crew, the social structure, learning and training, cooperative activity, and the overall goals of the task. Analyses and remedies that look at isolated segments are apt to lead to local, isolated improvements, but they may also create new problems and difficulties at the system level" (1990, p. 2).

The aviation realm contains numerous documented case studies and research findings that detail the coordination breakdown between flight crews and automation. Tools that were supposed to serve the human operators and provided 'added functionality' actually present new challenges in terms of human factors, usability, and training. Woods and Sarter (1998) capture the user's perspective on the current generation of automated systems. It is best expressed by the questions they pose in describing incidents: "What is it doing now? What will it do next? How did I get into this mode? Why did it do this? How do I stop this machine from doing this?" (p. 5). Questions like this point to *automation surprises*.

A landmark paper from Parasuraman and Riley (1997) noted that designers tend to automate everything that leads to an economic benefit and leave the operator to manage the resulting systems. "Technical capability and low cost are valid reasons for automation *if there is not detrimental impact on human (and hence system) performance in the resulting system*" (emphasis added; p. 232). The need for better feedback about the automation's states was revealed in a number of 'controlled flight into terrain' (CFIT) accidents, in which the crew selected the wrong guidance mode, and indications presented were similar to when the system was tracking the glide slope perfectly. For example, an Airbus 320 crashed in Strasbourg, France, when the crew apparently confused the vertical speed and flight path angle modes. "Unfortunately, the ability to address human performance issues systematically in design and training has lagged behind the application of automation, and issues have come to light as a result of accidents and incidents" (1997, p. 232).

## C. AUTOMATION IS NOT A PANACEA – MUST BE GUIDED BY AN ARCHITECTURE

'Advanced automation' is frequently touted as a solution to accomplish tasks formerly performed by Soldiers, thereby allowing us to decrease the number of Soldiers manning a vehicle. The tendency has been to automate what is easiest and leave the rest to the operators. From one perspective, this dignifies the operators. However, it may lead to a "hodgepodge of partial automation, making the remaining human tasks less coherent and more complex than they would be otherwise be, and resulting in overall degradation of system performance" (Sheridan, 2002, 152).

The former approach, unconsciously championed by many systems, electronics, and software engineers, does not relieve a Soldier of tasks. Rather, it merely shifts manual tasks to more supervisory ones. Automation aids do not "simply supplant human but rather changes it, often in ways unintended and unanticipated by the designers of automation, and a result poses new coordination demands on the human operator" (Parasuraman, Sheridan, & Wickens, 2000, p. 286-287). A soldier may become a 'super-supervisor' trying to handle the leftover tasks as well as monitor that which has

been automated. The engineers' motivation is threefold, albeit noble. First is to make the system simpler and cheaper to engineer. Second, is to relieve the human operator, to reduce mental workload. Third, is to the make the system safer. Yet automation can have just the opposite effect in all three categories (Bainbridge, 1983 as cited in Sheridan, 2000).

Vehicles in the MGV fleet will be complex systems with considerable technology advances. In some cases, the technology might enable the complete automation of certain subsystems, functions, and/or tasks. In many cases, however, Soldiers will still be very much involved in system operations. To combat the increasing complexity and serious potential for information overloads, Rouse, Geddes, and Curry (1987) argued that two methodological issues must be addressed (explicitly or implicitly) before beginning the development of a support system concept: choose a *design methodology*, and adopt an *automation philosophy*.

Rouse et al. (1987) argue that any human-machine interface should involve a few common methodological ingredients: an understanding of the user-system interaction, human capabilities and limitations in performing the general tasks identified, and the potential barriers to using the interface. In addition, "use of advanced hardware and software technology should not be an end in itself; it should be the means to providing the desired functionality. At the highest levels, this desired functionality is dictation by the *automation philosophy* underlying the support system concept" (1987, p. 90). The automation philosophy is governed by the questions of <u>when</u> and <u>how</u> to automate, with the answers directly determining the roles of operators in systems. "The purpose of explicitly choosing an automation philosophy is to assure that the implications for operators' roles are specific and acceptable prior to system design. This is important because the *overall performance of complex systems depends heavily on human performance*" (italics added; 1987, p.91).

Rouse et al. caution against simply automating all that is possible, stating that "this technology-driven approach is understandable, but is increasingly unacceptable as the technology that is driving automation efforts becomes more likely to be incomprehensibly complex" (1987, p. 91). They argue for the adoption of an operator-

centered automation philosophy, which emphasizes human operators in control and technology that provides support, a concept that "requires a comprehensive architecture for an intelligent interface" (1987, p.92).

## D. STATEMENT OF THE PROBLEM

The FCS MGV fleet lacks an overarching, top-down approach to its human-automation interface scheme. With the current methodology and design approach, it can be considered doubtful that performance from a 2-soldier crew will be acceptable, thus making the human and crew performance a major risk factor in overall system performance. Given the current ORD requirement for a 2-soldier crew, we must design a human-automation interface model that can be applied to the MGV common crew station (CCS) to increase the probability that a two-soldier crew will be able to perform well enough to accomplish all of the functions and tasks asked of the total vehicle system (hardware, software, and humans) as part of the Army's Unit of Action (UA) doctrine.

While this thesis focuses on ways to solve real technical issues in the FCS MGV fleet, the model and analytical processes proposed, or similar approaches, certainly are necessary in a slew of complex systems in multiple domains (aviation, space, maritime, ground transportation, manufacturing, etc.). As a thorough literature review reveals, there are very few people thinking about an 'automation philosophy' to guide the complex interactions between humans and automation to ensure total system performance. So while the proposals here were developed for the FCS MGV fleet, they are in no way limited to that particular application.

## E. PROPOSAL

In response to the problem statement detailed above, a three-step solution is proposed. The first step is to develop a <u>qualitative model</u> to drive the functional architecture and the human-automation interface scheme on the MGV fleet. This is but *one way* (among several) to work toward the ORD requirement for a 2-soldier crew. But, even if the 2-soldier crew requirement is relaxed, a coherent plan for automation will help to ensure soldier performance and system effectiveness. The focus of the model will be to

ensure that a reduced-crew can perform *well enough* (not optimally) to accomplish all of the functions and tasks asked of the total vehicle system.

The second step will be to apply the interface scheme against selected parts of the CCS function/task analyses (provided by BAE human factors specialists in their Santa Clara, CA office). The function/task analysis (FA/TA) provides an overall reference on how the Army and the V.I. envision the total vehicle system to operate. As such, the FA/TA is currently indifferent as to the allocation of functions and tasks between the hardware/software components of the system and the human crew.

Lastly, it would beneficial to gain a quantitative understanding how the application of the qualitative model to a block of functions from the FA/TA will affect soldier performance in the common crew station. One way to quantify estimated human performance in a system still in conceptual design is to predict human mental workload via a task-network modeling program. In this case, we will model the updated task analysis in a modeling program called Improved Performance Research and Integration Tool (IMPRINT), provided by the US Army Research Laboratory's Human Research and Engineering Directorate (ARL/HRED). IMPRINT allows analysts to quantify operator mental workload via prediction of task-loading in the proposed vehicle system, a key aspect of overall human performance (see ARL/HRED, 2005; Mitchell, 2000). The goal of this quantitative modeling will be to predict whether the new human-automation interface scheme, as modeled in IMPRINT, will lower operator task-loading predictions. If the mental workload score predictions are lower after apply the new model of human-automation interface, we can reasonably argue that careful, continued application of the new interface model may allow for satisfactory 2-soldier performance in the final system design.

The proposed thesis will provide a top-down, overarching approach that enables engineers to explicitly define and design the interaction between proposed automation schemes and the human crew. In effect, it constitutes the design methodology and automation philosophy, as espoused by Rouse et al. (1987). With this tool in hand, the exact role of the Soldier operators as the central component of the vehicle systems is clearly understood well before the fielding of the vehicle systems. In this way, we can

take a step towards reducing workload peaks and improving human performance. It will also support attempts to achieve the current ORD requirement for a vehicle operable by a 2-soldier crew. This work is intended to contribute to the effort to ensure that vehicle systems in the MGV fleet can accomplish the overall unit mission and the FCS' mission as an acquisition program.

## F. METHODOLOGY OVERVIEW

The methodology is described in four parts. First, it was necessary to conduct a comprehensive review of the Army's doctrinal concepts for the Unit of Action and Unit of Employment (UA/UE). FCS is the *materiel solution* to meet the UA/UE concept of future warfare, or how the Army wants its soldiers and units to fight in the future. To understand the materiel requirements, it is vital to thoroughly understand the fighting doctrine that FCS is being built to achieve.

The second major phase was to conduct a thorough review of the current ORD, the UA Operational and Organizational (O&O) Plan, the prime item development specifications (PIDS) and procurement control drawing (PCDs) for each of the vehicles being developed by the Army in conjunction with the Lead Systems Integrator (LSI) team of Boeing and SAIC. This family of doctrine, requirements, and specifications documents served to form the core of an overall 'human-automation interface' requirements listing and top-down requirements and functional analysis that was needed for the design phase of this thesis. Thus, the project required a thorough review in performing functional and task analyses (e.g., Kirwan & Ainsworth, 1992). Human factors specialists at BAE have already developed a fairly mature FA/TA for the common crew station (CCS), and developed a functional flow that was used in this project.

The third phase was to conduct a thorough literature review of automation design methodologies, especially as they relate to potentially reducing manning requirements (Chapter II). Two great examples of the military Services attempting to use 'advanced automation' to gain manpower savings are the Army's LHX helicopter program (which later became the RAH-66 Comanche), and the Navy's DD-X program. This phase formed the basis for the qualitative model proposed in Chapter III. In short, a 5-stage model for

types and levels of automation is proposed, both in textual and graphical form. The 5-stage model was applied against a selected group of functions from the CCS FA/TA provided by engineers at BAE-SC. Primary sources for the qualitative model include Parasuraman, Sheridan, and Wickens (2000), Parasuraman (2000), Endsley and Kaber (1999), Kaber and Endsley (2004), Proud, Hart, and Mrozinski (2003), and Billings (1997).

The fourth phase of the thesis was a quantitative task-loading analysis of the new human-automation interface in IMPRINT. Analysts with BAE-SC and ARL/HRED have developed a task-network model in IMPRINT using a set of functions common to the entire MGV fleet. Using their model as a baseline, I applied the proposed human-automation interface scheme to their selected portions common function model (CFM) to investigate whether predictions of total mental workload would decrease. This phase of the thesis was designed to demonstrate, quantitatively, how human task loading might be affected by a new human-automation interface scheme.

The proposed human-automation interface scheme for the MGV fleet can contribute to multiple HSI and MANPRINT (Manpower and Personnel Integration) domains that will require trade-off analysis to resolve. We can anticipate impacts to nearly all of the domains, including Manpower, Personnel, Training, Human Factors Engineering, Soldier Survivability, and System Safety (see US DoDI 5000.2, pp. 32-33, and US Army Regulation 602-2 for details of the HSI/MANPRINT domains and their definitions). The potential HSI (MANPRINT) domain tradeoffs will be discussed in Chapter VI.

## G. DEFINITION OF TERMS

A comprehensive list of acronyms appears on pages xiii-xv. However, there are several terms that must be defined now since they lie at the heart of the problem statement, methodology, and literature review.

<u>Automation</u> – Device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator (Parasuraman et al., 2000).

Key Performance Parameter (KPP) - KPPs are those attributes or characteristics of a system that are considered critical or essential to the development of an effective military capability.

Human Systems Integration (HSI) – comprehensive management and technical program that focuses on the integration of human considerations into the systems acquisition process.

MANPRINT – acronym for Manpower and Personnel Integration, the US Army's implementation of HSI that focuses on the integration of human considerations into the system acquisition process to enhance soldier-system design, reduce life cycle ownership costs, and optimize total system performance.

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# II. REVIEW OF THE RELEVANT LITERATURE

## A. UNIT OF ACTION (UA), UNIT OF EMPLOYMENT (UE), AND FUTURE COMBAT SYSTEMS (FCS)

### 1. UA/UE Doctrine and the 'Quality of Firsts'

Prior to beginning a rigorous systems engineering and capabilities needs process that will produce FCS, it is imperative to thoroughly understand the fighting doctrine that the Amy envisions for the Year 2015 and beyond. The Army's Training and Doctrine Command (TRADOC) argues that an increasingly demanding operational environment (OE) points to the necessity to build a "ground force designed for rapid deployment and operations across the full spectrum of war" (US Army TRADOC, 2003).

To do this, TRADOC envisions two major echelons of combat formations: the Unit of Action (UA), and the Unit of Employment (UE). UEs will be tailorable, higher-level echelons (what we now know as division, corps, and echelons above corps) that integrate and synchronize Army, Joint, and Multinational forces for full spectrum operations at higher operational levels of war. They link ground and joint forces and orchestrate ground operations that decide joint campaigns. UEs will focus on major operations and decisive land campaigns in support of joint operational and strategic objectives.

Units of Action (UA) will be the tactical warfighting echelons of the Army's Future Force (analogous to what we now call brigade and below). One or more UAs may fight under the command and control of a UE. The UA will fight battles; the UE will orchestrate multiple engagements to win battles. The function of the UA is to close with and destroy enemy forces though integrated fire and maneuver, and tactical assault. UAs will initiate operations to gain information superiority and fully understand the terrain, weather, enemy, and friendly forces; then turn that knowledge to advantage (US Army TRADOC, 2002).

There are two key concepts in this brief discussion of the UA that are pertinent. First, formations in the UA will be enabled be a 'Quality of Firsts'—See First, Understand First, Act First, and Finish Decisively. UA capabilities will permit future

commanders to "develop the situation before making contact, maneuver to positions of advantage and, when ready, initiate decisive action by destroying enemy systems beyond the range of their weapons to set the conditions for decisive assault and the UA's ability to develop situations out of contact" (US Army TRADOC, 2003, p. 1-2). The second key concept, already alluded to, is that UAs must develop the situation *out of contact*, without the need to first find and fix the engaged enemy force (US Army TRADOC, 2002). This is a leap-ahead operational paradigm, to be enabled by new and emerging technologies. In the past, ground maneuver units conducted 'maneuver to contact' in order to find and fix the enemy, putting the formation at significant risk. The UA concept directs that Army forces will find and understand the enemy prior to establishing contact, and then act before the enemy has a chance to put the formation in harm's way.

How does this UA/UE doctrine pertain to FCS? Simply put FCS is the *materiel solution* to meet the UA/UE concept of future warfare, or how the Army wants its soldiers and units to fight in the future. To understand the materiel requirements, it is vital to thoroughly understand the fighting doctrine that FCS is being built to achieve. FCS is conceived to enable the networked UA to "develop the situation in and out of contact, set conditions, maneuver to positions of advantage, and to close with and destroy the enemy through standoff attack and combat assault" (US Army TRADOC, 2003, p. 1-3). As described in Chapter I, the FCS Family of Systems (FoS) includes a planned fleet of manned ground vehicles that will provide specific functions in support of the operational concept. "The manned systems will provide capabilities that will enable many of the key operational parameters of the FCS force, including lethality overmatch, assured survivability and battle command on the move. Essentially, these [manned] systems contribute to the synergy that facilitates the 'quality of firsts'" (US Army UAMBL, 2005, p. D-1).

### 2. FCS ORD

To understand the capabilities and requirements that the US Army and the LSI are trying to develop with FCS, especially as it pertains to various automation designs in the MGV fleet, it is necessary to thoroughly review the FCS ORD. The ORD places many requirements and needed capabilities on the MGV fleet and associated network, far too

many to review in this thesis. There is an implicit assumption in the FCS program is expecting the development and maturation of a number of advanced automation technologies that can be integrated in the overall FoS and the MGV fleet.

The FCS ORD (see US Army UAMBL, 2005, Annex D) calls for eight manned platforms that provide specific functions in support of the operational concept: Mounted combat system (MCS), Infantry carrier vehicle (ICV), Non-line-of-sight cannon (NLOS-C), Non-line-of-sight mortar (NLOS-M), Reconnaissance and surveillance vehicle (RSV), Command and control vehicle (C2V), Medical vehicle (treatment and evacuation variants; MV-E and MV-T), and the FCS Recovery and Maintenance Vehicle (FRMV). Figure 3 outlines the fleet in development. The approach is to maximize commonality of these platforms, to include a common crew station (CCS) among all eight vehicles. Also of particular importance to this thesis is the requirement that the manned systems must be operable by a 2-man crew (a driver and vehicle commander). The current lone exception is the MCS variant which has been approved for an increase to a 3-soldier crew. IMPRINT analysis by Mitchell, Samms, Henthorn, and & Wojciechowski (2003) was the primary driver of this increase.

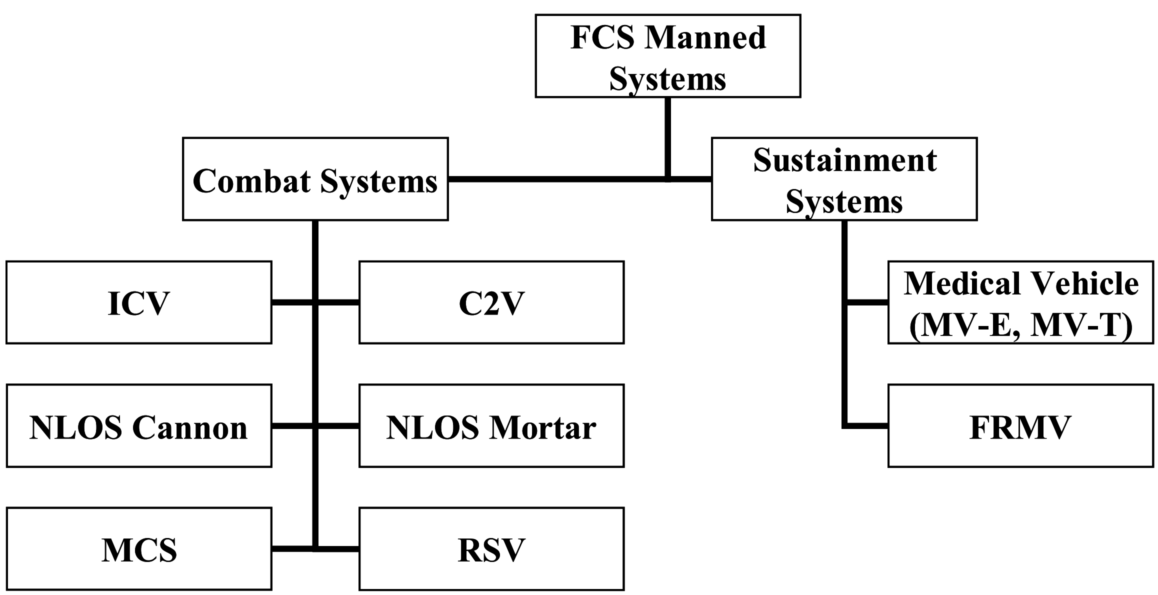


Figure 3. FCS Manned Ground Vehicle (MGV) Fleet

To gain an appreciation for the breadth and width of the requirements placed on the MGV fleet, and the implicit demands for highly advanced automation that must follow, here is a list of four major requirements placed on the common crew station:

- Wireless, remote operation of the vehicle by a dismounted crewman
- Control of unmanned systems and their payloads/mission packages (including unmanned aerial vehicles and unmanned ground systems)
- Control other manned platforms through robotic, non-mechanical tether (up to six vehicles)
- Operable by one crewmember for limited periods of time

Each one of these ORD requirements would require a major systems engineering and R&D effort to achieve the desired automation design. Undoubtedly, the V.I. team will assign knowledgeable, dependable, multidisciplinary teams of engineers and scientists to work on each requirement. However, it is safe to say that each team will take a significantly different approach to achieving their goal. The result will be four totally different schemes to describe the resulting interaction between the human crew and the hardware/software automation design. Thus, the burden will be placed on the operators, as well as the training system, to gain a full understanding of how each of these modes will operate.

Beyond the four examples of automation modes highlighted above, there are dozens of calls for advanced automation design on the MGV fleet throughout the ORD, both explicit and implicit. Several examples are: embedded sensor suites, physiological monitoring, weapons engagements, cooperative engagements, chemical-biological hazard detection, signature management, laser detection, automatic internal lighting, air self defense against multiple aerial targets, automated mission planning, acquisition and prioritization of multiple targets, monitoring and analysis of multiple supply needs, embedded prognostics and diagnostics for maintenance, automated preventative maintenance checks, decision aids to facilitate maintenance planning, and the list goes on. As an extension of the argument in the previous paragraph, the V.I. team will employ dozens of dedicated engineers and scientists in a strenuous attempt to meet these requirements. However, each person or team will likely work independently of each other and develop their own overarching architecture for their piece of automation. Some may

attempt to explicitly design the interaction between human and automation, but many will not. The results will be dozens of different schemes, explicit or implicit, to describe the resulting interaction between the human crew and the hardware/software automation design. Ultimately, it will be up to the FCS training system and the Soldier to learn and understand the many different modes of operation. This may well make it more difficult for soldiers to achieve acceptable operations or maintenance performance in the vehicle system (though we have yet to empirically prove this).

## B. HISTORICAL EXAMPLES OF AUTOMATION VS. MANNING LEVELS

The Army's FCS is by no means the first attempt to make the tradeoff between advanced automation design and the promise of reduced manning levels in extremely complex systems. There are four historical examples reviewed in an attempt to acquaint the reader with other major technology systems that were heavily concerned with the use of automation and the resulting manpower and human performance concerns, both in and out of the US DoD. They include a European nuclear power plant, a NASA project, the US Navy's DD-X, and ending with the Army's LHX program.

### 1. Nuclear Power Plant – Balancing Automation and Human Action

In a case study of a specific nuclear power plant in Europe, Fewins, Mitchell, and Williams (1992) reviewed the assessment of the plant's operation to ascertain whether proposed staffing levels were adequate. The primary objective was to assess "whether automation provisions with the design system would enable a specified plant manoeuvrre to be adequately carried out given the minimum main control room (MCR) staffing complement of one supervisor and one desk operator" (Fewins et al., 1992, p. 241). Additional objectives included identifying requirements for man-machine interface, work organization, training, and procedures; HSI/MANPRINT practitioners will recognize the similarity to the domains of human factors engineering, manpower, personnel, and training. They conducted a hierarchical task analysis, timeline analysis, and workload assessment to meet their objectives.

Their analysis strongly indicated that the workload assessed was within the capability of an increased staff of two desk operators and a supervisor, provided that

limited developments to the automation were adopted. However, the workload was much too high for the minimum staffing complement (one operator and one supervisor) without widespread automation, which was not considered practicable because of safety implications and projected cost. They recommended an additional desk operator in the staffing complement. Fewins, et al. (1992) also concluded that limited automation was an acceptable option for reducing operator workload in selected functions and tasks. The use of their methodology provided useful recommendations for the automation of parts of the control process, as well as man-machine interface design, and procedures and training.

### 2. Advanced Automation in Spaceflight Systems

Despite its acknowledged potential, advanced automation is rarely used in spaceflight systems, because many managers consider intelligent control systems an unacceptable risk. A group of NASA researchers make the case for introducing more advanced automation into spaceflight systems by defining systems engineering practices that improve reliability and earn trust (Freed, Bonasso, Ingham, Kortenkamp, Pell, & Penix, 2005). They argue that automation reduces dependences on people in potentially advantageous ways that can pay off as reduced staffing and training costs. In addition, onboard automation "can perform actions that would otherwise be performed by the crew" (Freed et al., 2005), enable reduced crew size requirements among other potential benefits.

Freed et al.'s vision of advanced automation allows goal-based commanding of system activities, in contrast to timed action-sequence commanding traditionally used. They also argue for variable autonomy, or the ability of intelligent control software to supports changes in degree of automation. The goal of variable autonomy software architecture is to allow systems to operate with dynamically varying levels of independence, intelligence and control. "A human user, another system, or the autonomous user itself may adjust the system's 'level of autonomy' as required by the current situation" (2005, p. 6). A key conclusion from their arguments is that variable autonomy is necessary for any application of autonomous control technology that *needs to interact with humans* [emphasis added]. "Humans who rely on the autonomous control

systems will want to be able to take control of it at various times and at various levels" (2005, p. 8). Their concepts on variable autonomy play a key part in the model of human-automation interaction proposed in this thesis.

### 3. US Navy's Manning Affordability Initiative and the DD-X

Engineers and scientists with the US Navy conducted a program in 1995-2000 called the Manning Affordability Initiative (MAI) which aimed to provide the "processes, tools, interaction guidelines, and procedures required to optimize a combat systems environment for the warfighter at reduced manning levels" (US Navy, 2002). The goal of the program was at least a 50% manpower reduction while demonstrating operational utility for all functions and maintaining or improving a ship's operational performance.

In a series of papers advocating an HSI approach to achieving reduced manning levels on future US Navy ships, there emerged three main themes to achieve reduced manning. First, move many functions currently performed by the ship's crew off the ship. Second, accept increased levels of risk by eliminating or consolidating some watch stations and reducing some support and hotel services. Finally, the point to the need to invest in emerging technologies that would reduced the number of sailors need onboard navy ships (Bost & Galdorisi, 2004; see also Malone & Bost, 2000; Hamburger, Bost, & McKneely, 1999).

The group went on to argue for the selective insertion of technology (i.e., automation) to enhance operator performance or substitute for manpower, with "human supervision of automated processes and human selection of automation levels. With the advent of 'smarter' systems that work cooperatively with human supervision, the role of many warfighter shifts from manual control and data input towards strategic thinking and planning. This shift in design focus may allow one operator to supervise processes and systems that were previously controlled by two, three, or more operators. Thus, automation must be planned carefully and designers must not necessarily take the human out of the information loop just because the control loop is removed in a mission process." (Bost & Galdorisi, 2004, p. 8).

Another key aspect from the Navy's MAI is the explicit call for a top-down function analysis (TDFA) and top-down requirements analysis (TDRA). Bost, McKneely, and Hamburger (1998) call the TDFA a process that evaluates which tasks should be down manually and which should be done with automation. Typically, the human element is not considered in the TDFA, leading to systems that do not account for human capabilities or limitations. They argue for tools such as better allocation of functions, function decomposition, and workload assessment, to name a few. Similarly, a TDRA is concerned with identifying, analyzing, and integrating requirements for missions, system functions, and human involvement in the performance of functions. In addressing approaches to reduce system manning, "simply automating system functions will not provide the warfighter with what he or she needs to monitor, plan, react, understand, maintain situation awareness, supervise, make decisions, make judgments, and modify plans due to changes in the tactical situation" (Malone & Bost, 2000, p. 1). The go on to argue for the TDRA as the HSI process for defining human requirements early in system development. "The only viable approach to optimal manning reduction is to develop a system where human and machine synergistically and interactively cooperate to conduct the mission, and where the automated systems supports human performance…." (2000, p. 1).

Before we close with our review of the Navy's MAI and reduced-manning programs, it is important to draw attention to the Navy's DD(X) program, a family of Navy ships with a peculiar and unique requirement: they must be manned by a mere 95 sailors, one-third the usual size of current or previous ships in a similar mission class. In fact, the manning requirement is a Key Performance Parameter (KPP) on the DD(X) program, a huge boon the HSI practitioners involved with the program and the MAI. Since manning is a KPP on the DD(X) program, it will gain serious attention, engineering effort, resources, and manpower since the DD(X) program manager and the Navy must prove that the DD(X) can perform to published standards with a severely reduced crew complement. This fact is important to note because the 2-soldier crew requirement on the Army's FCS MGV fleet is not a KPP, and so far has not gained a comparative attention

and engineering effort to prove that its vehicles can be operated by only 2 soldiers (as compared to the traditional 4 soldiers or more).

**4. The US Army's LHX Program**

The reduced manning goals in FCS' MGV fleet are by no means the Army's first attempt to realize manpower savings via the promise of advanced automation. Perhaps the most ambitious helicopter development program ever undertaken by the US Army was the LHX (for Light Helicopter, Experimental), a system that eventually became the RAH-66 Comanche. The Army originally conceived the LHX as a 7500-lb aircraft requiring only a single crewmember, an advantage that would result in a smaller target profile, as well as realize considerable manpower savings over the life-cycle of the system. Of course, design for single crewmember operations would require considerable effort and expense to automate many systems operations and functions. Army helicopters with similar missions have always employed two crewmembers, a pilot and gunner/observer (both rated aviators). In effect, the Army's goal was to introduce such advanced automation as to replace a human operator and reduce crew size by 50%.

Rigorous analyses by the Army Research Institute Field Units at Fort Rucker, Alabama (home of the US Army Aviation Center) looked into human performance data while evaluating various automation options, as well assessing the feasibility of operating the LHX with a single crewmember. In a landmark publication, McCracken & Aldrich (1984) developed an analytical process for evaluating human task-loading in the LHX under 29 different mission scenarios, effectively predicting mental workload via computational analysis. In fact, the analytical process developed by McCracken and Aldrich is a precursor of today's IMPRINT software. The results of their study concluded that the human in a single-pilot aircraft would become overwhelmed in critical situations (i.e. weapons engagements), even with considerable theorized automation help. Further analysis predicted that a dual-crewmember aircraft would experience multiple overload conditions in 22 of 29 mission segments, thus requiring some automation even with two operators in the cockpit.

In addition to the analysis at Fort Rucker, the Army established the Crew Station Research and Development Facility (CSRDF) at NASA's Ames Research Center at

Moffett Field in Mountain View, CA with the express purpose of evaluating technologies and human performance to determine whether single-pilot operations were feasible in the LHX. Despite considerable efforts at Fort Rucker, the US Army Aviation Systems Command in St. Louis, Missouri, and the CSRDF at NASA-Ames, by late 1987 the data available on LHX crew performance was pointing towards the need for a dual-crewmember setup. Accordingly, the LHX Program Manager went the US DoD Acquisition Executive and recommended a flat decision to continue development with a two-crewmember crew station that was single-pilot operable (personal communications, Dr. Michael McCauley, July 2005; James Minninger, October 2005; Dr. Harold Booher, October 2005; see also Booher, 1997).

#### 5. The US Army's Previous Crew Reduction Efforts for Ground Vehicles

Before the thesis closes the review on previous examples of manning vs. automation, it is correct to note that the Army has been looking at reduced manning in its ground vehicles for some time. The US DoD Human Factors Engineering Technical Advisory Group (HFETAG) has been looking at reduced manning for ground vehicles since at least the mid-1980s. A review of the meeting minutes from the HFETAG website (http://hfetag.dtic.mil) shows that several of the HFETAG meetings in the past twenty years had presentations on crew size reduction in armored vehicles.

An extension of the 1980s HFETAG crew reduction efforts is the Crewman's Associate Advanced Technology Demonstration (CA-ATD) sponsored by the US Army's Tank-Automative Command (TACOM). Active during 1994-2003, the CA-ATD focused on the integration of the crew and electronic subsystems into current and future vehicles, accomplished through the development of advanced crew stations which would increase crew performance and reduce crew workload. The CA-ATD program also focused on ways to create a two-man crew station while maintaining combat effectiveness. Many of the products and results of the program are being incorporated into the MGV fleet designs (personal communications, Dr. Patty Lakinsmith, July 2005; see also Karjala, 2001).

Lastly, the US Army nearly fielded a tank-like vehicle with a three-man crew (versus the standard four-man) in the mid-1990s. The M8 Armored Guns System (AGS) was designed to be an air-droppable, lightweight gun system, but only required a crew of three through the use of an autoloader (a mostly physical, vice cognitive, function previously performed by the fourth crewmember). However, the program was terminated in 1996 and abandoned, ostensibly due to budget issues. Incidentally, the AGS is an example of a program in which MANPRINT considerations were purposely rejected; it is not a coincidence that the Army canceled the program (see Booher, 2003, p. 667; Federation of American Scientists, 2000).

## C. FUNCTION ALLOCATION

At the heart of these previous examples of automation design versus possible manpower reduction has been the concept of function allocation (FA). Its main aim is to provide a rational means of determining which systems-level functions should be carried out by humans and which by machines. As technology has progressed over the past several decades, many purchasers of advanced (and expensive) defense weapons systems have made the not-unreasonable assertion that advanced technology can take over many tasks and functions previously done by human beings—the most variable, unpredictable, and expensive part of the overall system. "Function allocation tries to balance attempts to mechanize or automate as many system functions as possible by seeking roles and tasks for humans that makes the best use of their capabilities while recognizing human limitations" (Beevis, Essens, & Schuffel, 1996, p. 1). Function allocation is linked to issues of automation and manpower reduction, as well as to questions about human responsibility for the safe and effective operation of a system.

In 1951, Dr. Paul Fitts edited and prepared a report titled *Human Engineering for an Effective Air-Navigation and Traffic Control System.* In this report he created two lists, one defining what man is better able to accomplish, and another listing what machines are better able to accomplish. This seminal contribution to the literature effectively started the discipline known as Function Allocation. By the late 1950s, the Fitts' List approach of comparing human and machine capabilities had been incorporated

into a number of human engineering guidelines (Beevis, Essens, & Schuffel, 1996). This approach grew into what became known as the MABA-MABA (Men are Better At—Machines are Better At) lists. This general approach was the primary way to determine function allocation within a system.  Table 1 lists the relative capabilities originally developed by Fitts and adapted from Sheridan (2002) and Fuld (2000) (as cited in Wickens, 1992, p. 429).

Table 2. "Fitts' List" Showing the Relative Benefits of Automation and Humans

| *Humans are better at* | *Automation is better at* |
|---|---|
| Detecting small amounts of visual, auditory, or chemical signals (e.g., evaluating wine or perfume) | Monitoring processes (e.g., warnings) |
| Detecting a wide array of stimuli (e.g., integrating visual, auditory, and olfactory cues in cooking) | Detecting signals beyond human capability (e.g., measuring high temperatures, sensing infrared light and x-rays) |
| Perceiving patterns and making generalizations (e.g., "seeing the big picture") | Ignoring extraneous factors (e.g., a calculator doesn't get nervous during an exam) |
| Detecting signals in high levels of background noise (e.g., detecting a ship on a cluttered radar display) | Responding quickly and applying great force smoothly and precisely (e.g., autopilots, automatic torque application) |
| Improvising and using flexible procedures (e.g., engineering problem solving, such as on the Apollo 13 moon mission) | Repeating the same procedure in precisely the same manner many times (e.g., robots on assembly lines) |
| Storing information for long periods and recalling appropriate parts (e.g., recognizing a friend after many years) | Storing large amounts of information briefly and erasing it completely (e.g., updating predictions in a dynamic environment) |
| Reasoning inductively (e.g., extracting meaningful relationships from data) | Reasoning deductively (e.g., analyzing probable causes from fault trees) |
| Exercising judgment (e.g., choosing between a job and graduate school) | Performing many complex operations at once (e.g., data integration for complex displays, such as in vessel tracking) |

Despite the marvelous simplicity of the Fitts List, most practitioners and researchers seem wholly unsatisfied with the progress of the FA discipline as a whole over the past five decades. This general guideline to FA was, at the time, a proactive approach to embedding concerns for human capabilities and limitations in systems and provided a sense of direction for the discipline. However, this historical approach and its practice in the ensuing decades came to be an unrealistic and outdated concept, never fully developing into a useful concept. A 1992 NATO research group called FA the weakest in a group of six human engineering analysis techniques (Beevis, Essens, & Schuffel, 1996), and the *International Journal of Human-Computer Studies* dedicated its

entire February 2000 special issue to review the status of FA. The workshop drew the following conclusions [Beevis et al., 1996, p. xix]:

- Problems with terminology remain, particularly when human factors specialists communicate with those in other engineering disciplines
- FA is not an isolated activity and must be incorporated in the development process early enough to influence design decisions and to permit iteration
- No single technique is available that deals with all of the issues involved in assigning functions
- FA decisions must be validated by predictions of operator workload or system performance and the allocation decisions revised if necessary in an iterative approach
- Little research activity is devoted currently to human behavior in systems operations or to improving human factors engineering techniques

Perhaps the most telling quote comes from Sheridan, concluding that FA practitioners are "obliged to continue our efforts to underpin what is essentially an artful design synthesis with a modicum of science (2000, p. 204).

## D. AUTOMATION DESIGN IS NOT AN 'ALL-OR-NONE' CONCEPT – LEVELS OF AUTOMATION

### 1. Levels (Degrees) of Automation

While the Fitts list gives a useful starting point to think about the allocation of functions between human and automation (hardware and/or software), many layman tend to see the allocation as an 'all-or-none', black-or-white, binary affair. The function or task is either completely manual or completely automatic, with nothing in between. We can point to robotized factories as a popular example in the media, with little mention of the associated programming, monitoring, fault detection and diagnosis, and maintenance functions performed by humans (Sheridan, 1992, 2002). The truth, at the heart of this thesis, is that humans and automation will work together as part of the FCS Family of Systems. "The human and computer can interact in an infinite number of ways, resultant

in an infinite spectrum of allocation possibilities from which to choose" (Sheridan, 2002, p. 58).

Automation can vary across a "continuum of levels, from the lowest level of fully manual performance to the highest level of full automation" (Parasuraman, Sheridan, & Wickens, 2000, p. 287). Table 3 shows the 10-point scale with higher levels representing increased autonomy of the machine over the human. For example, at a low level 2, several options are provided to the human, but the system has no further say in which decision is chosen. At level 6, the system automation gives the human only a limited time to override before carrying out the decision. Each level carries with it additional opportunities for machine error; each precludes human intervention to a greater extent.

Along with the scale that he largely developed, Sheridan (1992) anticipated that for some tasks, we are happy to let the computer go all the way, while for others we would prefer to limit automation at a level well down in the list. The tendency has been to automate what is easiest and to leave the rest to the human. "From one perspective, this dignifies the human contribution; from another it may lead to a hodgepodge of partial automation, making the remaining human tasks less coherent and more complex than they need be and resulting in an overall degradation of system performance" (Sheridan, 1992, p. 358).

Table 3. Levels of Automation of Decision and Action Selection (Parasuraman, Sheridan, and Wickens, 2000).

| | |
|---|---|
| High | 10. The computer decides everything and acts autonomously, ignoring the human |
| | 9. Informs him or her after execution if it, the computer, decides to |
| | 8. Informs him or her after execution only if he or she asks, or |
| | 7. Executes automatically |
| | 6. Allows the human a restricted time to veto before automatic execution, or |
| | 5. Executes that suggestion if the human approves, or |
| | 4. Suggests one, and |
| | 3. Narrows the selection down to a few, or |
| | 2. The computer offers a complete set of action alternatives, or |
| Low | 1. The computer offers no assistance; the human must do it all |

## 2. A Model for Types and Levels of Automation

Along with this 'Levels-of-Automation' (LOA) approach, Parasuraman, Sheridan, and Wickens (2000) extended the concept to cover automation of different types of function in a human-machine system. The scale in Table 3 refers mainly to "automation of decision and action selection, or output functions of a system. However, automation may also be applied to input functions, i.e. to functions that precede decision making and action" (2000, p. 287). Thus, in expansion of the LOA concept, they proposed a four-stage view of human information processing (Figure 4).

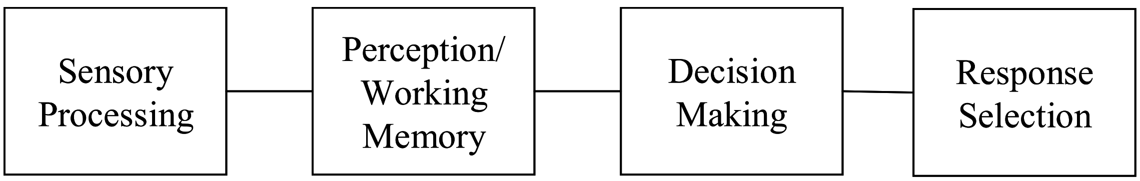


Figure 4. Simple four-stage model of human information processing (Parasuraman, et al., 2000)

By their own admission, this four-stage model is almost certainly a "gross oversimplification of the many components of human information processing" (2000). However, their structure is useful in practice, and provides a "simple starting point with surprisingly far-reaching implications" for designing the interaction scheme between a human and automation. They go on to reason that the four-stage information processing model of has "its equivalent in systems functions that can be automated" (2000). They further proposed that automation can be applied to four classes of function (see also Sheridan, 1998; Billings, 1997; Lee & Sandquist, 1996):

1. information acquisition
2. information analysis
3. decision and action selection
4. action implementation

Each of these functions can be automated to differing degrees, or many levels. The multiple levels of automation of decision making (as shown in Table 2) "can be applied, with some modification, to the information acquisition, information analysis, and

action implementation stages as well" (Parasuraman, et al., 2000, p. 288). Students and fans of the late Colonel John Boyd, US Air Force, may appreciate how the four broad functions of this model are analogous to the infamous Observe-Orient-Decide-Act (OODA) loop commonly used by defense and business personnel around the world (see Boyd, 1996).

The particular advantage of the Parasuraman, Sheridan, and Wickens model is the simple schematic they provide for model types and levels of automation (Figure 5). A particular system can involve all four dimensions at different levels. Thus, for example, a given system (A) could be designed to have moderate to high acquisition automation, low analysis automation, low decision automation, and low action automation. Another system (B), on the other hand, might have high levels of automation across all four functions (2000). Their graphical representation of a human-automation interface scheme makes it particularly easy to envision the overarching functional architecture of a system, to see exactly how a human will interact with the designed automation. Like slider bars on your stereo equalizer, systems and human factors engineers can 'slide up' or 'slide down' the level of automation in each major function of a particular, thereby explicitly specifying *how the human will interact with the automation.*

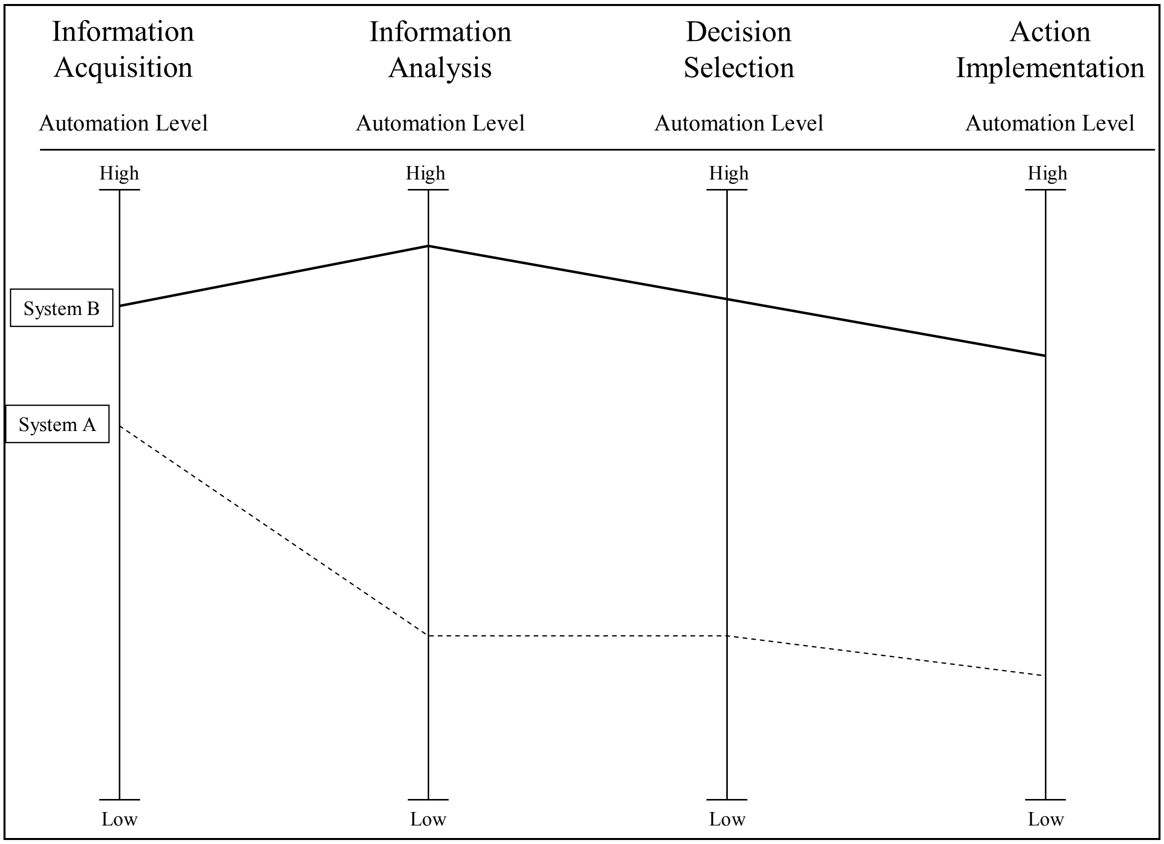


Figure 5. Levels of automation for independent functions of informationm acquisition, information analysis, decision selection, and actin implementation. Examples of two systems with different levels of automation across functional dimension are also shown (Parasuraman et al, 2000).

The model they outlined provides a "framework for examining automation design issues for specific systems" (2000, p. 289). They proposed a series of steps and an iterative procedure for examining which system functions should be automated and to what extent. They go on to argue that the human performance consequences of specific types and levels of automation constitute the "primary and secondary evaluative criteria for automation design using the model" (2000, p. 286). Their primary evaluative criteria include mental workload, situation awareness, complacency, and skill degradation. Secondary evaluative criteria include automation reliability and costs of decision/action outcomes. All of these should be applied "to evaluate the feasibility and appropriateness of particular levels of automation" (2000, p. 289) in an iterative process.

In a closely related paper published at the same time, Parasuraman (2000) also discusses the types-and-levels model as a qualitative approach to human-automation interaction design. However, he also goes on to argue for the development of quantitative models that could inform the design of human-automation interaction, pointing out several computational and formal models of human interaction with automation. For example, if available, such models "could address the major issue in the design of effective human-automation interaction, namely the determination of the specific type and level of automation in a particular system….There may be tradeoffs in benefits and costs involved in different levels of automation and choosing the level that maximizes the overall gain may be guided by quantitative models" (2000, p. 940). He concludes that "an important future research need is the integration of qualitative and quantitative models" (2000, p. 946) which should provide for a more objective basis for a determining effective modes of human interaction with automation.

Overall, the model presented in Parasuraman et al. (2000) and Parasuraman (2000) is the foundation for this thesis, as will be illustrated in Chapter III. Starting with their model for types and levels of automation, the proposed qualitative model blends ideas from three other research teams, each of which is discussed below. Beyond that, the urging from Parasuraman (2000) to blend in a quantitative approach gives rise to the use of IMPRINT from ARL/HRED as a way to predict operator task-loading once the proposed qualitative model is applied to a system in development.

## E. OTHER LEVELS-OF-AUTOMATION RESEARCH

### 1. Kaber & Endsley Using a Dynamic Control Task

In addition to the four-stage model proposed by Parasuraman, Sheridan, and Wickens, there are two other major research teams that have proposed level-of-automation taxonomies similar in scope and intent. The first major thrust comes from Endsley and Kaber (1999; see also Endsley & Kaber, 2004; Kaber, Endsley, Wright, & Warren, 2002). These researchers developed a 10-level taxonomy applicable to a wide range of psychomotor and cognitive tasks, as well as numerous work domains, with four

generic functions that can be allocated to a human operator and/or a computer. The functions are:

1. Monitoring: taking in all information relevant to perceive system status
2. Generating: formulating options or task strategies for achieving goals
3. Selecting: deciding on a particular option or strategy
4. Implementing: carrying out the chosen option through control actions at an interface

In their work, ten LOAs were systematically formulated by assigning these four functions to the human or computer, or a combination of the two, as shown in Table 3.

Table 4. LOA Taxonomy for human-computer performance in dynamic, multitask scenarios (Endsley & Kaber, 1999; Kaber & Endsley, 2004)

| Level of Automation | Functions | | | |
|---|---|---|---|---|
| | **Monitoring** | **Generating** | **Selecting** | **Implementing** |
| (1) Manual Control | Human | Human | Human | Human |
| (2) Action Support | Human/Computer | Human | Human | Human/Computer |
| (3) Batch Processing | Human/Computer | Human | Human | Computer |
| (4) Shared Control | Human/Computer | Human/Computer | Human | Human/Computer |
| (5) Decision Support | Human/Computer | Human/Computer | Human | Computer |
| (6) Blended Decision Making | Human/Computer | Human/Computer | Human/Computer | Computer |
| (7) Rigid System | Human/Computer | Computer | Human | Computer |
| (8) Automated Decision Making | Human/Computer | Human/Computer | Computer | Computer |
| (9) Supervisory Control | Human/Computer | Computer | Computer | Computer |
| (10) Full Automation | Computer | Computer | Computer | Computer |

Kaber and Endsley (2004, p. 115) contend that their LOA taxonomy provides several advantages over previous/historical hierarchies of LOAs. It provides greater detail on 'who' (the human or computer) is doing 'what' at each LOA." Furthermore, the list (Table 3) does not "focus only on decision making and defining authority." The key advantage is that it allows "careful empirical assessment of which aspects of automation might be helpful or harmful to human performance in conjunction with [the proposed] system." They cite the Parasuraman et al. (2000) model for LOA design, but point out that their own model considers the option generation (planning) function, instead of the information analysis function in the Parasuraman et al. model. However, the other three functions in the Parasuraman et al. model are identical to the monitoring, selection, and implementation features of the Kaber & Endsley taxonomy (see Table 4).

Table 5. Comparison of Taxonomies: Parasuraman, Sheridan, & Wickens vs. Kaber & Endsley

| **Parasuraman, Sheridan, & Wickens (2000)** | | **Kaber & Endsley (2004); Endsley & Kaber (1999)** |
|---|---|---|
| Information Acquisition | = | Monitoring |
| Information Analysis | = | |
| | = | Generating |
| Decision Selection | = | Selecting |
| Action Implementation | = | Implementing |

In the three publications cited from the team of Kaber and Endsley, they drew a number of conclusions regarding automation design and LOAs. In Endsley and Kaber (1999), their research explored various LOAs in the context of a dynamic control task as a means of improving overall human/machine performance. Results suggest that, in terms of performance, "human operators benefit most from the implementation portion of the task, buy only under normal operating conditions" (1999, p. 462). In addition, joint human/automation option generation significantly degraded performance in comparison to human or automated option generation alone.

A follow on study from Kaber and Endsley (2004) examined the effects of LOAs in interaction with adaptive automation in a similar dynamic control task. Again, results revealed LOA to be the driving factors in determining primary task performance. "The results are supportive of intermediate LOAs…as approaches to human-centered automation" (2004, p. 113). The empirical results from these studies, combined with other LOA empirical research (such as Ruff et al., 2002, below), give us some guidelines for choosing LOAs in new human-automation systems under development. The results give us an initial target for the proper LOA and at the proper function to gain improved human performance in the human-automation interaction.

### 2. LOA Taxonomy from NASA

The other major LOA taxonomy in the literature is a four-stage model from Proud, Hart, and Mrozinski (2003) out of the National Aviation and Space Administration's (NASA) Johnson Space Center in Houston, TX. These engineers were

seeking to shift, where appropriate, several functions from humans to an autonomous flight management (AFM) system, encapsulated in a prototype call SMART (Spacecraft Mission Assessment and Re-planning Tool). SMART is a “functionally decomposed flight management system with an appropriate level of autonomy for each of its functions” (2003, p. 1), but Proud et al. needed a method to determine the appropriate level of autonomy for each function within a system. Starting with Sheridan’s degrees of automation scale (1992; see Table 2) and then moving to the Parasuraman et al. (2000) four-stage model already discussed, they realized that the AFM functions fell into a similar four-tier system using the terms monitor, analyze, decide, and act.

They correctly realized one of the limitations of the LOA scale (Table 2) in that Sheridan’s 10-LOA scale refers mainly to automation of decision and action selection, or the output functions of a system. Automation may also be applied to the input functions of system, i.e. the information acquisition, information analysis, and even option generation functions. They then integrated aspects of Boyd’s OODA loop (Boyd, 1996) to develop an 8-level level of autonomy scale to determine how to assign a level of autonomy for a particular function (Figure 6).

| Level | Observe | Orient | Decide | Act |
|---|---|---|---|---|
| 8 | The computer gathers, filters, and prioritizes data without displaying any information to the human. | The computer predicts, interprets, and integrates data into a result which is not displayed to the human. | The computer performs ranking tasks. The computer erforms final ranking, but does not display results to the human. | Computer executes automatically and does not allow any human interaction. |
| 7 | The computer gathers, filters, and prioritizes data without displaying any information to the human. Though, a program functioning" flag is displayed. | The computer analyzes, predicts, interprets, and integrates data into a result which is only displayed to the human if result fits programmed context (context dependant summaries). | The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the human. | Computer executes automatically and only informs the human if required by context. It allows for override ability after execution. Human is shadow for contingencies. |

| Level | Observe | Orient | Decide | Act |
|---|---|---|---|---|
| 6 | The computer gathers, filters, and prioritizes information displayed to the human. | The computer overlays predictions with analysis and interprets the data. The human is shown all results. | The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human. | Computer executes automatically, informs the human, and allows for override ability after execution. Human is shadow for contingencies. |
| 5 | The computer is responsible for gathering the information for the human, but it only displays nonprioritized, filtered information. | The computer overlays predictions with analysis and interprets the data. The human shadows the interpretation for contingencies. | The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human. | Computer allows the human a context-dependant restricted time to veto before execution. Human shadows for contingencies. |
| 4 | The computer is responsible for gathering the information for the human and for displaying all information, but it highlights the non-prioritized, relevant information for the user. | The computer analyzes the data and makes predictions, though the human is responsible for interpretation of the data. | Both human and computer perform ranking tasks, the results from the computer are considered prime. | Computer allows the human a pre-programmed restricted time to veto before execution. Human shadows for contingencies. |
| 3 | The computer is responsible for gathering and displaying unfiltered, unprioritized information for the human. The human still is the prime monitor for all information. | Computer is the prime source of analysis and predictions, with human shadow for contingencies. The human is responsible for interpretation of the data. | Both human and computer perform ranking tasks, the results from the human are considered prime | Computer executes decision after human approval. Human shadows for contingencies. |
| 2 | Human is the prime source for gathering and monitoring all data, with computer shadow for emergencies. | Human is the prime source of analysis and predictions, with computer shadow for contingencies. The human is responsible for interpretation of the data. | The human performs all ranking tasks, but the computer can be used as a tool for assistance. | Human is the prime source of execution, with computer shadow for contingencies. |
| 1 | Human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) all data. | Human is responsible for analyzing all data, making predictions, and interpretation of the data. | The computer does not assist in or perform ranking tasks. Human must do it all. | Human alone can execute decision. |

Figure 6. Level of Autonomy Assessment Scale (Proud, et al., 2003, p. 4)

The scale from Proud et al. they developed in Figure 6 also highlights one of the key elements missing from the Parasuraman et al. model (2000): the Parasurman et al. model lacked useful descriptions of what the exact interaction between human and

automation is supposed to be at each level of automation in each the functions. The intent of the Proud et al. (2003) scale is "to help system designers easily and correctly identify the level of autonomy to design each function within their system. They are available for either identifying the level of autonomy of an existing function or for proposing an appropriate level of autonomy during the design of a new system. The OODA category aspect of this scale is advantageous because: 1) it allows more specific verbal description of the level of autonomy of a specific function than previous scales, and 2) it allows the function types to be weighted differently across a particular level. The second point is important to understanding the scale as a whole. A 5 in the Act column does not have the same costs, training requirements, or other assumptions as a 5 in the Orient column" (Proud et al., 2003, p. 5). The table developed by Proud et al. (2003) figures prominently in the proposed qualitative model along with the Pararsuraman et al. model (2000).

### 3. LOA Research for Multiple UAVs

Ruff, Narayanan, and Draper (2002) reported on an evaluation that compared effects of LOA and decision-aid fidelity on the number of UAVs that could be successfully controlled by one operator during a target acquisition task. Their LOAs included manual control, management-by-consent, and management-by-exception. The three LOAs corresponded to automation levels 1, 5, and 6 (respectively) from the Parasuraman et al. (2000) model (see Table 2). Dependent variables included mission efficiency, percentage correct detection of incorrect decision aids, workload and situation awareness (SA) ratings, and trust in automation ratings. Results indicated that an automation level incorporating management-by-consent (Sheridan LOA-5) had some clear performance advantages over the more autonomous (management-by-exception; LOA-6) and less autonomous (manual control; LOA-1) levels of automation. LOA-5 kept workload under control even with the operator controlling two or four UAVs, and SA scores were superior for LOA-5 across the number of UAVs controlled.

Ruff et al. concluded that workload "does not abate as human tasks are automated" (2002, p. 348). Increasing automation to management-by-consent (LOA-5) maintains human-in-the-loop system functionality, but it reduces human responsibility for functions that humans do poorly (e.g., vigilant monitoring). Increasing automation to

management-by-exception (LOA-6) further removes the human from the decision-making process, lowering SA and making it more difficult for the human to make decisions when he or she is finally called upon. "Therefore, the foremost recommendation that stems from this study is the importance of an active role of the human operator in complex system decision-making processes" (2002, p. 348).

# III. QUALITATIVE MODEL FOR THE DESIGN OF A HUMAN-AUTOMATION INTERFACE OF SYSTEM FUNCTIONS

## A. FIVE-STAGE MODEL FOR TYPES AND LEVELS OF AUTOMATION IN THE FCS MGV FLEET

Given the available literature on design of automation and the opportunity to participate in the FCS MGV program through BAE-SC, a qualitative model is proposed to drive the functional architecture and the human-automation interface scheme on the MGV fleet. With this tool in hand, the exact role of the Soldier operators as the central component of the vehicle systems is clearly understood before the fielding of the vehicle systems. This is *one way* (among several) to work toward the ORD requirement for a 2-soldier crew. But, even if the 2-soldier crew requirement is relaxed, a coherent plan for automation will help to ensure soldier performance and system effectiveness. The focus of the model will be to ensure that a reduced-crew can perform *well enough* (not optimally) to accomplish all of the functions and tasks asked of the total vehicle system.

The model proposed starts with Table 5, a five-stage model of information processing for the human-automation interaction scheme in the FCS MGV fleet. It stands squarely on the shoulders of a few giants in the field of human factors and automation research and development. It starts with the four-stage model proposed by Parasuraman et al. (2000) (see Figure 4). In addition, the LOA taxonomy from Endsley & Kaber (1999) (see Table 3) highlights the fact that option generation is an important facet of information-processing scheme for the MGV fleet and its soldier-operators (see Table 4).

However, the term ‘generation’ from Endsley & Kaber (1999) does not quite capture the flavor of information-processing scheme in these Army vehicles. Instead, we turn to Army Field Manual 5-0 about the doctrine for the military decision making process (MDMP; see US Army, 2005). Army doctrine uses the term ‘Course of Action (COA) Development’ to describe both the generation and analysis of strategies to accomplish a mission, function, or task. So the five-stage model proposed in Table 5 borrows the term ‘COA Development’ to better describe the particular function and lend the proper Army flavor to this model.

Table 6. Five-Stage Model of Information-Processing for Human-Automation Interaction Scheme in the FCS MGV Fleet

| ***Stage*** | | ***Definition*** |
|---|---|---|
| **1** | **Information Acquisition** | Acquisition and registration of multiple sources of information. Positioning and orienting of sensory receptors, sensory processing, initial pre-processing of data prior to full processing, and selective attention |
| **2** | **Information Analysis** | Conscious perception and manipulation of processed and retrieved information in working memory. Also includes cognitive operations (rehearsal, integration, and inference) occurring prior to point of decisions. |
| **3** | **COA Development** | Generating (a) the decisions that need to be made, followed by (b) formulating options or task strategies for achieving goals. |
| **4** | **Decision Selection** | Selection of a particular option, course of action (COA), or strategy to carry out. Decision(s) are reached based on the Analysis stage (cognitive processing), the COA Development stage, and expertise (human or software). |
| **5** | **Action Implementation** | Consistent with the decision selection(s), carrying out the chosen option, COA, or strategy, whether through control actions at an interface or other means. |

Following the simple schematic from the Parasuraman et al (2000) model shown in Figure 4, the proposed human-automation interface model is shown graphically in Figure 7. This figure demonstrates the five stages of information processing, as well as the possibility for ten LOAs within each of the five stages. It retains the intuitiveness of the original model while allowing system engineers and designers to explicitly define how the human and proposed automation will interact. Hopefully, this approach will enable better understanding of how the two will perform as part of the overall system in development. We will return to a discussion of Functions A/A′ and Systems B/B′ momentarily.

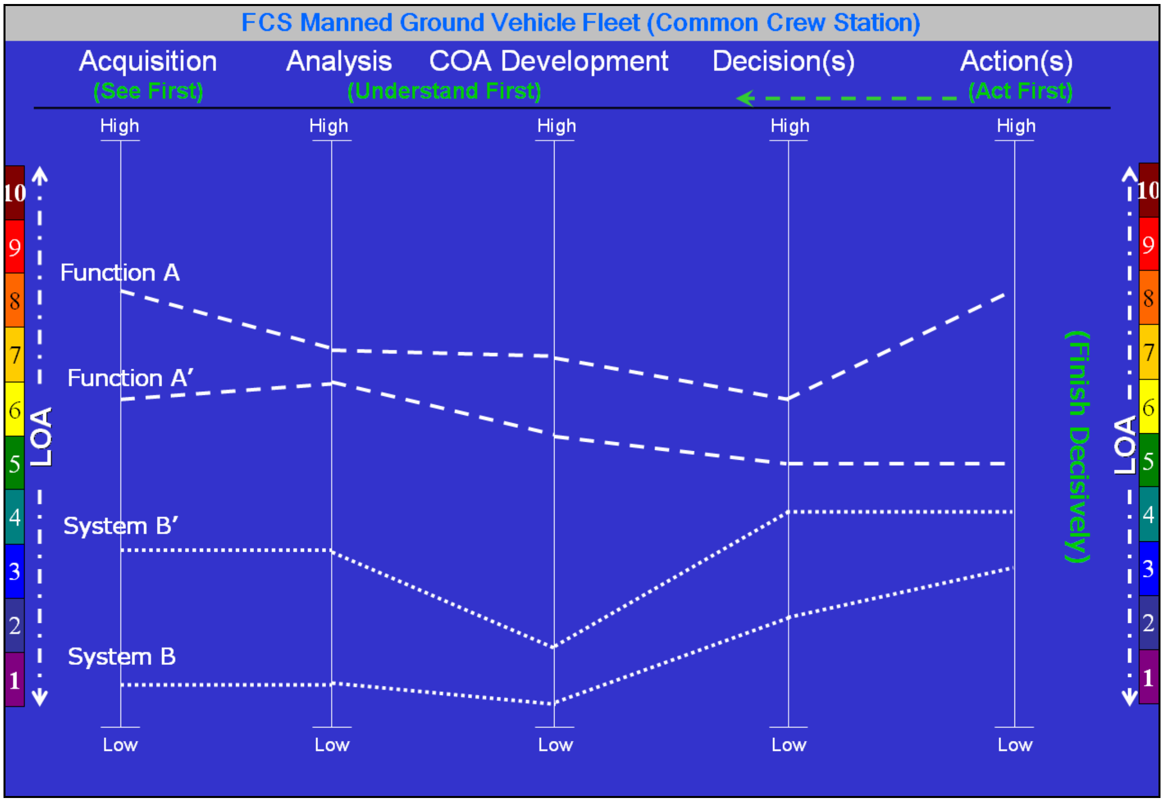


Figure 7. Qualitative Model for Design for Human-Automation Interaction in the FCS MGV Fleet. Note how the UA 'Quality of Firsts' are related to the proposed model.

The final segment of the proposed human-automation interface model borrows from the Proud et al. (2003) model. Table 6 contains a description of the proposed interaction between human and automation at each function of the five-stage model (Table 5) at each LOA. The descriptors in Table 6 are intended as an aid to system engineers and designers to understand the subtle changes in human-automation interaction with each change in LOA at each function. For instance, as a designer thinks about moving from LOA 3 to LOA 6 in the Analysis stage, he will have this table of descriptors to help understand the implications of that shift in terms of human-automation behaviors, roles, and responsibilities. The table's descriptors also illustrate how human-automation compares between two different stages while at the same LOA.

Table 7. Descriptors for each LOA at each of the 5-stages of the proposed model

| Level | Information Acquisition | Information Analysis | Generation | Decision(s) Selection | Action Implementation |
|---|---|---|---|---|---|
| **10** | Automation uses internal and external sensors to gather, filter, and prioritize data without displaying any information to the human operator. | Automation predicts anticipated future events using information from objects in the environment, interprets and integrates data. Results are not displayed to the human. | Automation generates the decision(s) to be made and the COAs available. Rank orders the best choice (based on internal algorithm). Does not display to the human operator. | Automation selects best choice from its own list of COAs. Does not display selection justification process or choice to human operator | Automation carries out decision(s) autonomously without delay. Human is completely out of the loop, and no intervention is possible. System does not even display that action is being implemented. |
| **9** | Automation uses internal and external sensors to gather, filter, and prioritize data w/o displaying any information to the human. Only displays "program functioning" flag to confirm system status; human monitors system status via flag, and takes over sensors if necessary (essentially moving down one level). | Automation is an 'information manager' that predicts, interprets, and integrate data into a result which is only displayed to the human if result fit programmed context (context-dependent summary) | Automation generates decision(s) to be made and applicable COAs. Displays best option to human operator only if asked for it. | Automation selects best choice from its own list of COAs. Displays the selection process only if required by context. | Automation executes action w/o delay and only informs the human if required by context (or if automation decides to). No override or intervention is possible(?) |
| **8** | Automation uses internal and external sensors to gather, filter, and prioritize data w/o displaying any information to the human. On request, displays status of sub-systems (sensors, comm. links, weapons, links, etc) for human to monitor. | Automation is an 'information manager' that predicts, interprets, and integrates data into a result (context-dependent summary) which is only displayed if asked for by the human. Information integration augments human operator perception and cognition. | Automation generates decision(s) to be made and applicable COAs. Rank orders COAs for each decision. Displays list (up to 5) only if human asks for it. | Automation displays best choice from its own list of COAs. Displays selection process and result if asked by human operator. | Automation executes w/o delay and only informs human of action if asked for it. Override by human is possible after execution starts; human monitors for contingencies. |

| Level | Information Acquisition | Information Analysis | Generation | Decision(s) Selection | Action Implementation |
|---|---|---|---|---|---|
| **7** | Automation uses internal and external sensors to gather, filter, and prioritize data. Displays filter and prioritized information to human. Also displays sub-systems statuses for human to monitor. Automation has primary control over sensors to scan and observe; human can take over sensor placement. | Automation overlays predictions with analysis and interprets the data (simple summary, not context-dependent). The human is shown all of the results. | Automation generates decisions to be made and COAs. Rank order COAs (by embedded algorithm or criteria), and displays the best option to the operator. | Automation displays top recommended COA to human for yes/no decision. | Automation executes w/o delay, informs the human explicitly, and allows for override after execution. Human monitors for contingencies. |
| **6** | Automation responsible to gather data via sensors and links. Displays only highlighted, prioritized, relevant information, along with sub-systems statuses. Automation has primary control over sensors to scan and observe; human can take over sensor placement. | Automation overlays predictions with analysis and interprets the data. Human monitors the interpretation for contingencies. | Automation generates decision(s) to be made and COAs and displays in recommended rank order (up to 5 COAs) to human operator. Operator may generate additional decision(s) and COAs, but not for input to computer. | Automation displays up to 5 COAs in rank order, from which the human must choose. | Automation delays execution by a context-dependent amount of time that allows the human operator to veto the action before it is carried out. Human monitors for contingencies. |
| **5** | Automation responsible to gather data via sensors and links. Displays all data to human operator, but highlights prioritized, relevant information. Displays sub-systems statuses. Automation has primary control over sensors to scan and observe; human can take over sensor placement. | Automation analyzes the data and makes predictions. Human completes interpretation and integration into information. | Automation generates decision(s) to be made and COAs. Displays in recommended rank order (up to 5) to human operator. Human may generate additional decision(s) and COA(s) for input to computer. | Automation displays up to 5 COAs in rank order. Human chooses from this list, or from own list. | Automation delays execution by a pre-programmed (fixed) amount of time that allows the human operator to veto the action before it is carried out. Human monitors for contingencies. |

| Level | Information Acquisition | Information Analysis | Generation | Decision(s) Selection | Action Implementation |
|---|---|---|---|---|---|
| **4** | Automation responsible to gather data via sensors and links. Displays all data to human operator, but highlights non-prioritized, relevant information. Displays sub-systems statuses. Automation has primary control over sensors to scan and observe; human can take over sensor placement. | Automation is the prime source for analysis and prediction. Human monitors, and is responsible for prediction and integration of data into information. | Automation generates decision(s) to be made and COAs. Displays full list in recommended rank order to human operator. Operator may generate additional decision(s) and COA(s) for input to computer (if needed). | Automation displays full list of COAs in recommended rank order. Human can choose from this list, or from own list of COAs. | Automation executes after human operator explicitly approves. Human monitors for contingencies. |
| **3** | Automation responsible to gather data via internal and external sensors; has primary control over sensors to scan and observe. Displays unfiltered, unprioritized data to human operator; displays status of sub-systems (sensors, weapons, comm. links, CTP/COP). Human is still the prime monitor of all data; augments automation with own sensory receptors. Human has the ability to take over sensor placement from automation. | Automation is the prime source for analysis, displaying rudimentary results to monitoring operators. Human operator responsible for all prediction, interpretation, and integration. | Automation generates decision(s) to be made and COAs. Displays up to 5 COAs for each decision in random order to human operator (by design, or if ranking algorithm not available). Human may generate additional decision(s) and COA(s) for input to computer. | Automation displays up to 5 COAs in random order. Human selects from this list, or from his/her own list of COAs. | Human operator executes by minimal physical interaction (e.g. 1-2 switch actuation or button presses). Automation 'agents' track user interaction with computer and execute all sub-tasks automatically (i.e. batch processing). |

| Level | Information Acquisition | Information Analysis | Generation | Decision(s) Selection | Action Implementation |
|---|---|---|---|---|---|
| 2 | Human is the prime source for sensing, monitoring, and prioritizing data. Human positions sensors (own, internal, and external) as part of selection attention; has full control of sensors in order to scan and observe. Automation tracks status of relevant sub-systems (sensors, CTP/COP, weapons, comm links) but does not display; shadows for emergencies(?). | Human is the prime source for analysis, prediction, interpretation, and integration of data into information. Automation only displays raw data values from sensors and links to help human operator. | Automation generates decision(s) to be made and COAs. Displays full list of COAs for each decision in random order to human operator (by design, or if ranking algorithm not available). Human may generate additional decision(s) and COA(s) for input to computer. | Automation displays complete set of decision/ action alternatives. Human selects COA from the full list, or from own list of COAs. | Human operator executes by extensive, indirect physical manipulation of necessary sub-systems (e.g. teleoperation, remote operations, slaving of human physical action, virtual environments). |
| 1 | Human is the only source for sensing and registration of input data; filters, prioritizes, understands. | Human performs all perception and cognitive processing, making predictions and interpretation of data, or integrating several variables into a single value. No information available from automation. | Human operator generates decision(s) to be made and the available COAs. No assistance from automation. | Human selects choice from his/her own list of COAs, with no assistance from automation. | Human operator carries out the decision, directly and physically implementing all aspect of the chosen action with no interaction or help from automation. |

Referring back to Figure 7, let's look at the examples of Functions A/A′ and Systems B/B′ on the graphical scheme. Function A might represent one proposed way to describe the human-automation interaction for this particular function as it proceeds from information acquisition to analysis and on through to decision selection and action. System designers have deliberately designed this interaction as a way to understand how the two components will interact, and also to conceptually understand what exactly the

automation should be designed and built to do as it aids the human operator. However, they also would like to look at the alternative of Function A′, another way of deliberately describing the interaction. This example shows the utility of the proposed model as modified from Parasuraman et al. (2000) for the MGV fleet. The graphical representation of human-automation interface makes it particularly easy to envision the overarching functional architecture of a system or function to understand exactly how a human will interact with the proposed automation. Like the slider bars on your stereo equalizer, the designers could simply 'slide down' the LOA on several of the functions. Combined with the descriptors in Table 6, designers can clearly understand the new relationship between human and automation throughout the entire Function A/ A′. Likewise, System B/B′ may represent a much smaller system that can be looked at as whole from information acquisition through to the decision and action stages. In this case, designers might be thinking about introducing more automation to the small system, and can use the graphical representation in Figure 7 along with the descriptors in Table 7 to better understand the resulting relationship between human and automation in their new proposal.

## B. APPLICATION OF MODEL TO MGV FUNCTIONAL FLOW

The next step in the thesis is to exhibit how the proposed qualitative model might be applied against the functional flow that describes MGV operations. The human factors group at BAE-SC has developed a FA/TA and functional flow for the CCS of the MGV fleet. The FA/TA provides an overall reference on how the Army and the V.I. envision the total vehicle system to operate. As such, the FA/TA is currently indifferent as to the allocation of functions and tasks between the hardware/software components of the system and the human crew. Using the FA/TA and functional flow provided from BAE-SC engineers, Figure 8 shows a top-level view of the five functions envisioned for the CCS in what is being called the Common Function Model (CFM). The five functions thought to be common to the entire MGV fleet are vehicle movement (driving), communication, vehicle commander's awareness, driver's local surveillance, and local defense. This thesis will focus on applying the proposed qualitative human-automation interaction model to the last of these, the Local Defense function.

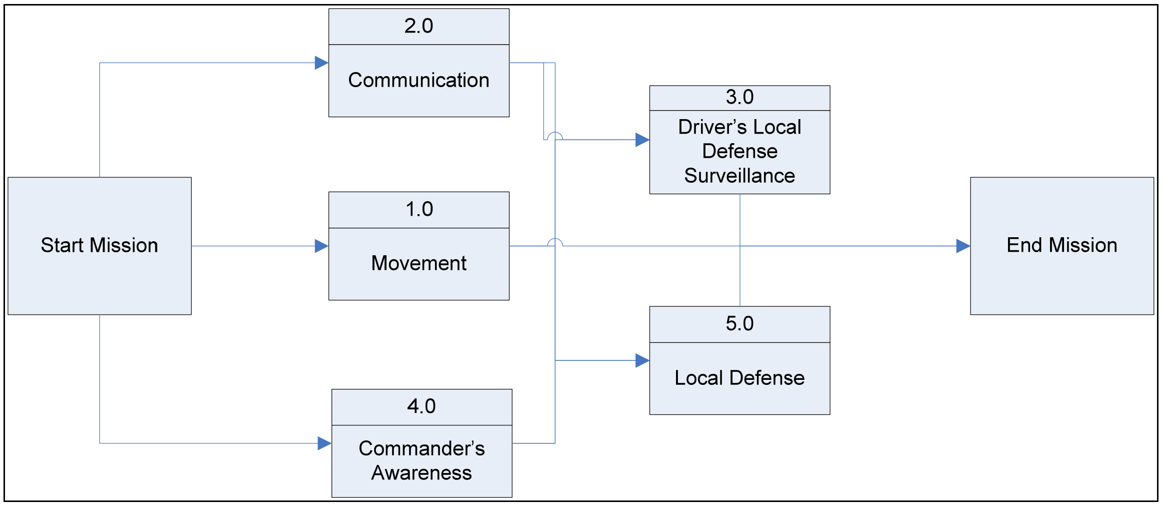


Figure 8. CFM Function Flow – Level 1.

Figure 9 shows a further decomposition of the functional flow to a secondary tier that will be called level two. Notice that the Function 5 (Local Defense) has two subfunctions called Acquire/Track Threat and Engage Threat.

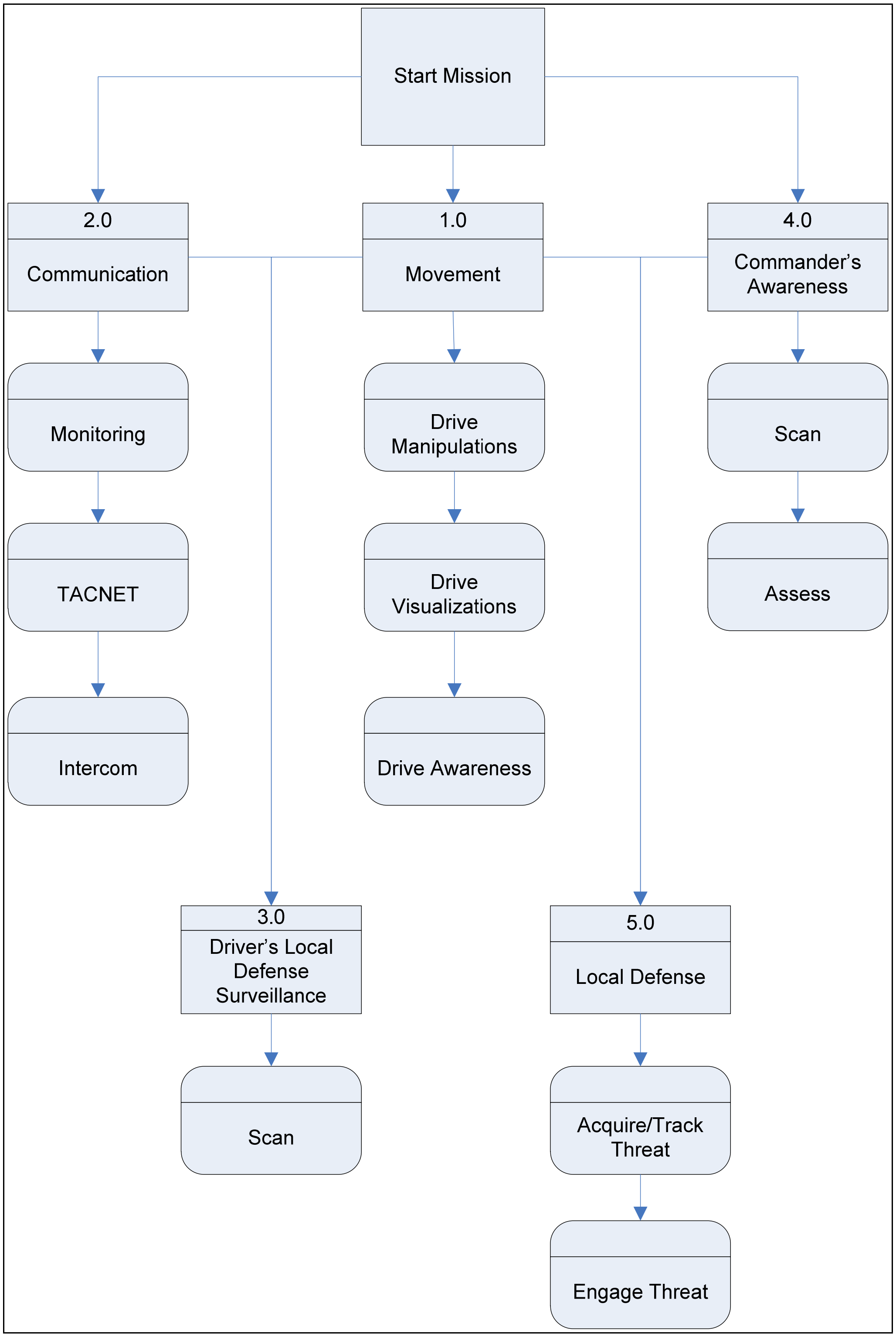


Figure 9. CFM Functional Flow – Level 2

Figure 10 shows a third-tier decomposition of the Local Defense only into a series of tasks; this is the final decomposition. The tasks contained in Function 5.1 (Acquire/Track Threat) are displayed underneath its bubble, as are the tasks for Function 5.2 (Engage Threat). The tasks involved preparing and transmitting a digital SITREP (situation report) are repeated in both tasks depending on the flow.

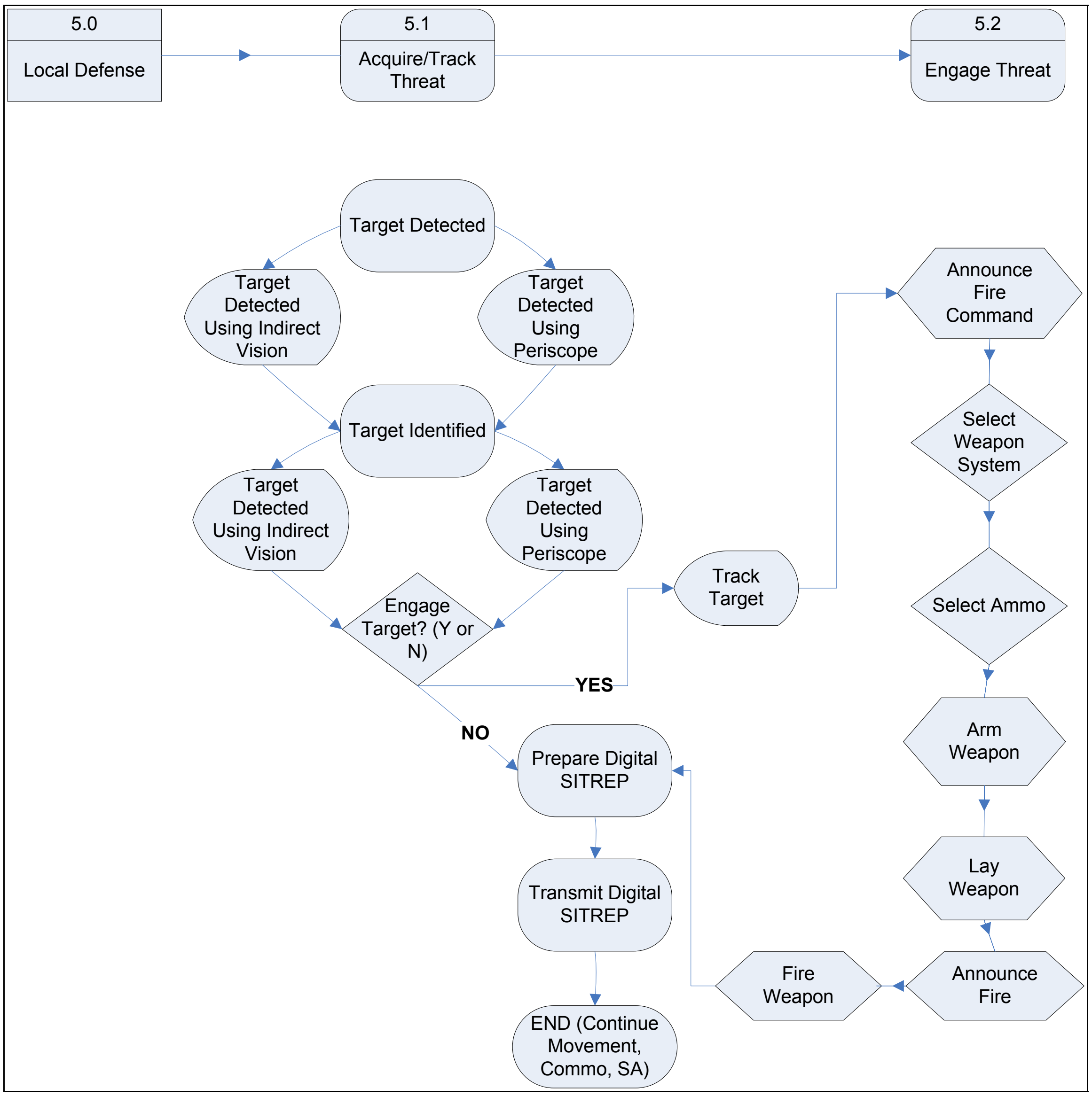


Figure 10. CFM Functional Flow – Level 3 – Function 5.0 (Local Defense)

Figure 11 goes one step further to collect the decomposed tasks into groups that adhere to the information processing model proposed in Table 5.

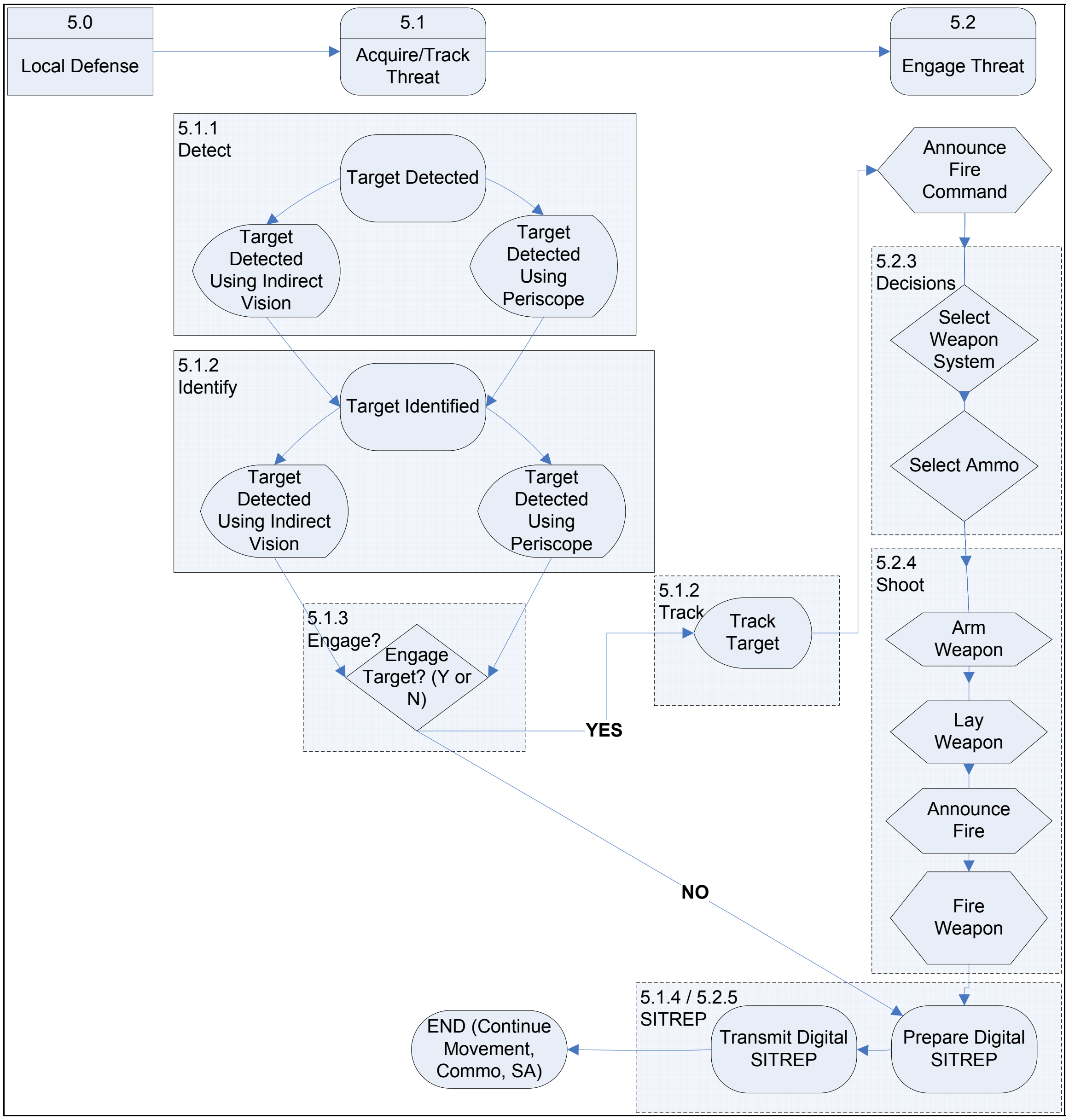


Figure 11. Local Defense (CFM Function 5.0), with tasks decomposed and grouped in accordance with the proposed information processing flow model

Using the functional flow for Local Defense graphically shown in Figure 11, the next step is to then apply it against the proposed model for MGV human-automation

interaction shown in Figure 7. The result is the proposed schematic in Figure 12. Here we can begin to understand the possible relationship between human and automation in the Local Defense function.

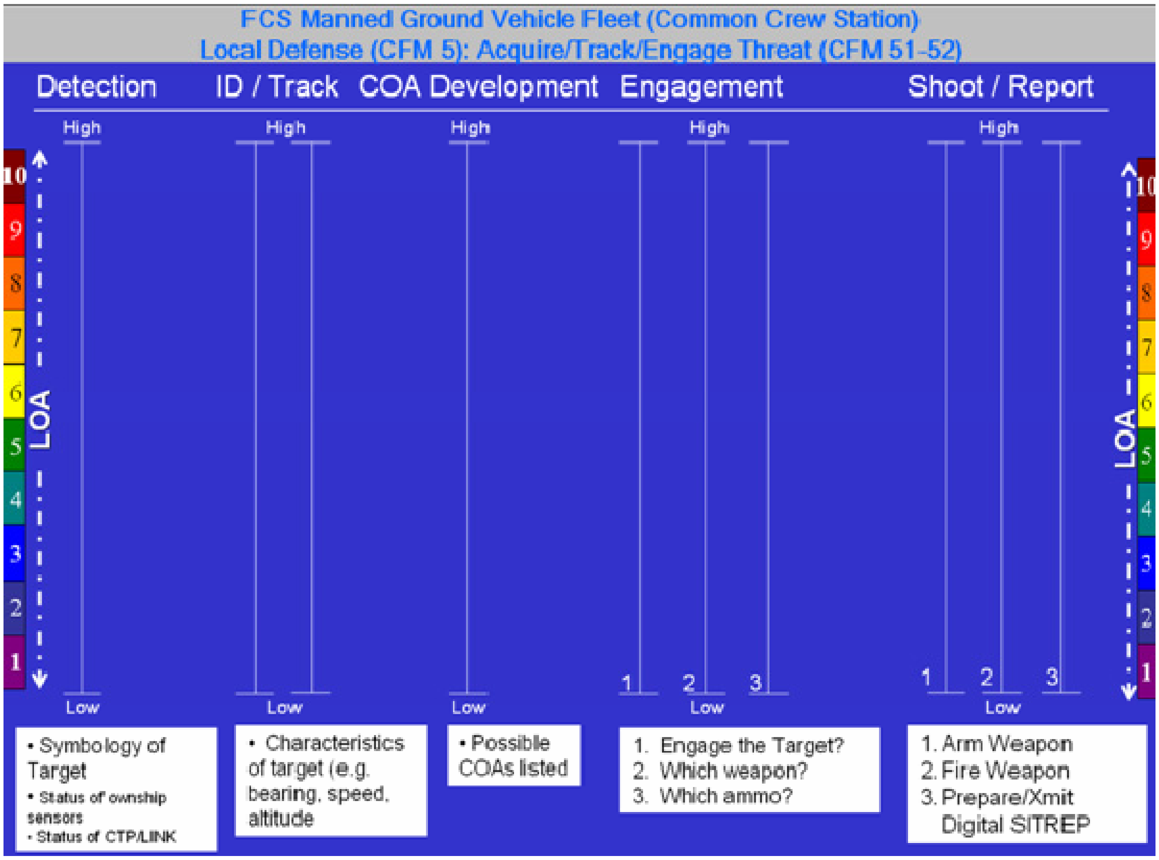


Figure 12. Local Defense (CFM 5) decomposed into the proposed qualitative model

At this point in the process, we can now begin to purposely design the interaction between the human operators and a conceptual automation scheme, or to quote Parasuraman et al., we can begin to ask "what level of automation should be applied within each functional domain. There is no simple answer to this question, and tradeoffs between anticipated benefits are likely" (2000, p. 289). The graphical model in Figure 12 and the descriptors in Table 7 are proposed as a guiding framework. Evaluative criteria will be discussed below, but three clusters of sources can help to begin the process. The first is prior empirical research, such as that reviewed earlier from Kaber and Endsley (2004) and Ruff et al. (2002). "To take a hypothetical example, suppose prior research has shown (or modeling predicts) that, compared to manual operation, both human and

system performance are enhanced by level 4 automation but degraded by automation above level 6” (Parasuraman et al, 2000, p. 290). This could serve as an initial specification for the upper and lower bounds of automation in a certain function. Research sources include the writings from experienced researchers in the field who have delved into real automation and resulting human accidents, such as Billings (1997), Norman (1990), Woods and Sarter (1998). The second cluster looks to Army doctrine and past experience from tactics, techniques and procedures (TTPs), which can guide us as to understanding what has (and has not) worked in past and current systems. Closely related is the third cluster, input from subject matter experts (SMEs). SMEs may be real soldiers who work in the combat development or material development structures for the Army. They can also include the experience and expertise of scientists and engineers who have been involved in systems design in the past, particularly human factors specialists.

Therefore, to further the ideals of this thesis, Figure 13 graphically presents two possible human-automation interface schemes to achieve the common function of Local Defense. The current scheme (yellow line on the graph) employs almost no automation at all, only giving the vehicle commander some physical aids to allow arming and firing of the chosen weapon with a single button press. The vehicle commander is totally responsible for detecting, identifying, and tracking any local threats. Unfortunately, the common FA/TA provided by BAE-SC does not account for the COA Development stage proposed in this thesis, so it is skipped and simply left at full manual control. In the Engagement stage, the commander must then make a series of decisions (probably in rapid order) that starts with whether to engage the target or not, followed by selections of the appropriate weapon and ammunition. At the Shoot/Report stage, automation design gives the commander some physical help by only requiring a simple button press to arm the chosen weapon, and then another single-button press to fire the weapon. Preparation and transmission of the digital (i.e. typed text) situation report is left completely with the commander.

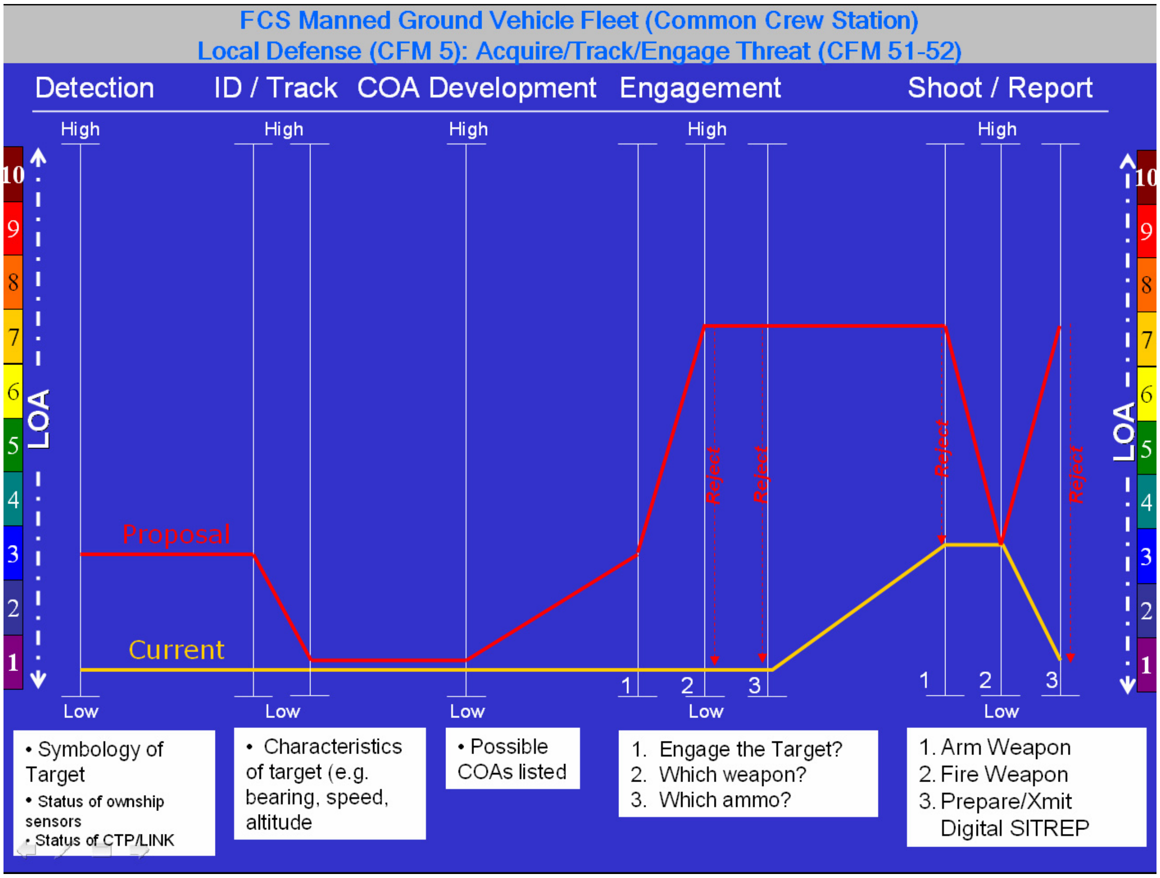


Figure 13. Qualitative Model Applied to the Local Defense Function

In contrast to the current scheme, a new proposal for human-automation is graphically represented in Figure 13 with the red line. Notice that, per the description of the model in Figure 7, the 'slider bars' are up to higher LOAs for certain tasks in the Local Defense function. The new proposal blends some prior research, some SME input, and some human factors knowledge.

Starting with the Detection and Identification tasks, the interface is moved up to LOA-3 in accordance with the descriptors in Table 6. Upon reflection about the Tracking task, it was decided that the soldier simply monitoring any proposed automation would require just as much mental workload effort and doing it himself, so it is left unchanged. Moving to the Engagement tasks, the human will get some help in making the decision to engage or not. After that, it is hypothesized that an intelligent automation scheme would quickly make the correct recommendation for the appropriate weapon and ammunition based on sensor data. If the commander decides not to engage the target, he would move

straight away to the SITREP preparation and transmission. Finally, as the functional flow continues, computer software would ask the commander if he wants to arm the chosen weapon. Then the commander can fire the weapon with a single button press (no change from the current scheme). To end the sequence, the commander would get considerable aid in preparing and transmitting the SITREP, a big change from the current system. Of course, the entire sequence feeds back on itself and repeats, as dictated by the operational situation.

There are four dashed arrows in the proposed human-automation scheme that require some explanation. For the two decisions at LOA-7, the proposed interface would entail the computer making a recommendation to the vehicle commander for a yes-or-no decision. If the human accepts the recommendation, the next task occurs. However, for these two decision tasks, if the commander *rejects* the recommendation, then the scheme reverts to LOA-1, the same as the current scheme. For the task of arming the chosen weapon, a similar scheme results. If the vehicle commander decides to reject (or override) the arming of the weapon, then the interaction reverts to LOA-1. Lastly, the computer will prepare a SITREP based on available data and transmit automatically unless the commander rejects (or overrides) the preparation/transmission task, causing a reversion to LOA-1.

The white boxes at the bottom of each of the five stages in Figure 11 depict basic pieces of information about what might be displayed to the vehicle commander at that stage of the functional flow. In the Detection stage, the commander will probably need to see the proper symbology of all targets, the status of his vehicle's sensors, and status of the common operational picture (COP), common tactical picture (CTP), and any communications links to the network. In the Identification/Track tasks, the commander will likely need to have further information about the target, such as location, bearing, speed, even altitude. Information for any of these stages may come from the vehicles own sensors, from the COP, or over the network. In the COA Development stage, the commander will need to see the possible COAs, depending on the LOA used. In a slight shift, the white boxes below the Engagement and Shoot/Report tasks each delineate

exactly what decisions have to be made, and what actions must be carried out. These decisions and actions can be accomplished by the *soldier-automation team.*

## C. APPLICATION OF MODEL TO LITTORAL COMBAT SHIP

The example detailed in the previous section is for only one function of the common crew station for the MGV fleet. In an attempt to provide the reader with another example of how this process might be carried out in another domain, Appendix B of this thesis contains an example of the Parasuraman et al. (2000) model of human-automation interface applied to the US Navy's Littoral Combat Ship.

The paper included in the Appendix was developed as a conceptual project for a course in Systems Engineering and Integration at the Naval Postgraduate. The paper was published in the proceedings of the 2005 Human Systems Integration Symposium (see Kennedy, Thomas, & Green, 2005).

## D. EVALUATIVE CRITERIA

Borrowing once again from Parasuraman, Sheridan, and Wickens (2000), any particular "level of automation should be evaluated by examining its associated human performance consequences. However, human performance is not the only important factor. Secondary evaluative criteria include automation reliability and the costs of decision/action consequences" (p. 289), though others may include ease of systems integration, efficiency/safety tradeoffs, issues of operators, and more. "These should be applied to evaluate the feasibility and appropriateness of particular levels of automation" (p.289), done in an iterative process. They emphasize, however, that the model should not be treated as a static formula or as a prescription that decrees a particular type or level of automation. Rather, when considered in combination with primary and secondary evaluative criteria, the model they provided, and expanded in this thesis, "can provide principled guidelines for automation design" (p. 289).

### 1. Primary Criteria

Over the past 25 years, researchers have found that automation can have both beneficial and negative effects on human performance. There are four main human

performance areas recommended by Parasuraman et al. (2000) as primary evaluative criteria: mental workload (MWL), SA, complacency, and skill degradation. Evidence suggests that well-designed information automation can change MWL to a level that is appropriate for the systems tasks being performed. However, “clumsy” automation can lead to increasing workload (2000). As will be discussed below, MWL can be modeled during system design to assess if it is reasonable throughout system functional flow.

Besides unbalanced MWL, automation can incur human performance costs in the other three criteria suggested. Situation awareness can be negatively affected when the operators loses “awareness of the system and certain dynamic features of the work environment” (2000, p. 291). If the MGV automation scheme is highly but not perfectly reliable in executing the major decision choices, “then the operators may not monitor the automation and its information sources and hence fail to detect the occasional times when then automation fails” (2000, p. 291) or is wrong. Complacency is greatest in high MWL setting when the operator is engaged in multiple tasks. Third, skill degradation can certainly occur over time if the system decisions are routinely carried out by the automation. “These potential costs—reduced situation awareness, complacency, and skill degradation—collectively demonstrate that high-level automation can lead to operators exhibiting out-of-the-loop unfamiliarity. All three sources of vulnerability may pose a threat to safety in the system failure” (2000, p. 291). The MGV automation design must demonstrate that potential human performance costs, along with unbalanced MWL, do not occur. “By considering these human performance consequences, the relative merits of a specific level of automation can be determined” (2000, p. 291).

### 2. Secondary Criteria

Secondary evaluative criteria can include automation reliability and the cost of decision and action outcomes. Reliability is typically defined in probabilistic terms, such as a reliability of .997 or a mean time to failure of 10,000 hours. In addition, “failures may occur not because of a predictable (in a statistical sense) malfunction in software or hardware, but because the assumptions that are modeled in the automation by the designer are not met in a given operational situation” (2000, p.292). The reliability of automation also influences human trust, possibly undermining potential system

performance benefits when the automation is underused or disabled. In addition to reliability, “assessing the appropriate level of automation for decisions requires additional consideration of the costs associated with decision and action outcomes” (2000, p. 292; see also Lee and See, 2004).

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# IV. THE HUMAN-AUTOMATION INTERFACE MODEL IN ACTION: A QUANTITATIVE IMPLEMENTATION VIA IMPRINT

## A. NEED FOR QUANTITATIVE MODELS

Parasuraman et al. (2000) correctly argue for the primary evaluative criteria as part of the design process for a human-automation interaction scheme. As discussed in Chapter II of this thesis, Parasuraman (2000) also argued for the development of quantitative models that could inform the design of human-automation interaction, pointing out several computational and formal models of human interaction with automation.

This thesis implemented the qualitative model applied to the MGV (per Chapter III) via a computational analysis using task-network modeling and Monte Carlo simulation from a software called IMPRINT (see below for details). This demonstration is a way to quantitatively predict human task-loading attempts to evaluate the primary criterion of mental workload. There is one example in the literature from Parasuraman et al. (2005) where a automation scheme has been modeled via a computational task-network model. In the study, the research team investigated the effects of a delegation-type interface on human supervision of multiple unmanned vehicles. As part of the experimentation program, they conducted analysis via WinCrew to carry out a mental workload prediction (personal communication, Dr. Hiroshi Furukawa, 20 Sep 05). WinCrew is a precursor to the program MicroSAINT, which is the heart of ARL/HRED's IMPRINT software. The Parasuraman et al. (2005) paper provided the inspiration to demonstrate the proposed MGV human-automation guidelines in IMPRINT.

## B. IMPROVED PERFORMANCE RESEARCH AND INTEGRATION TOOL (IMPRINT)

IMPRINT is a stochastic network-modeling tool designed to help assess the interaction of soldier and system performance from concept and design through field testing and system upgrades. An important feature of IMPRINT is that it helps researchers and designers evaluate operator and crew mental workload while testing

alternate system-crew function allocations. The amount of mental workload that is required to use a system has a significant effect on human performance within the system. IMPRINT gives system designers the information they need to predict how changes in design can affect overall system performance. Since FCS is still early in the design phase, IMPRINT is a very suitable tool to use (Mitchell, Samms, Henthorn, & Wojciechowski, 2003; Mitchell, 2005).

One major function of IMPRINT, via task-network modeling, is to predict operator task-loading using cognitive resources (visual, auditory, cognitive, motor, and speech) and Monte Carlo simulation. This provides quantitative values for total momentary workload based on the estimates of cognitive resources provided by the analyst. The IMPRINT methodology has a long history in the Army, originated during the early days of the LHX program as discussed in Chapter II. Without a doubt, the accuracy and precision of the modeling results depend on the skill and experience of the analyst (as they say, Garbage In—Garbage Out). However, it is a well accepted modeling methodology in use by multiple Army (and DoD) programs.

The task-network model in IMPRINT is generally run for a set period of time; anywhere from one minute to several hours, depending on the needs of the analyst. The models generated for this thesis were set to run for 60 minutes. To run the simulation for the set time, the analyst provides a random number seed to the program, an integer from 1-100,000. In effect, the random number seeds simulate the variation that would normally be provided by different human subjects. IMPRINT provides a host of numerical results straight to Microsoft Excel for further scrutiny. Chief among these is the total momentary workload score calculated each time a tasks begins or ends. The advanced workload feature of IMPRINT used in this analysis calculated workload based on the cognitive resources being used by the operator, and incorporates the fact that multiple tasks are being performed simultaneously.

Previous technical reports and publications from ARL/HRED using IMPRINT have incorporated a workload 'threshold' value where the operator was considered to be a state of 'high' or 'very high' workload. This concept of a workload threshold goes back to the original LHX analysis from McCracken and Aldrich (1984). The IMPRINT

workload value of 60 has been used by a consensus of workload modeling SMEs to represent the 'high' threshold, while the workload value of 100 is equivalent to the 'very high' threshold (Mitchell, Samms, Henthorn, & Wojciechowski, 2003; Mitchell, 2005).

Previous technical analysis by IMPRINT modelers for the FCS MGV fleet has yielded five metrics of use in the IMPRINT analysis: 1) maximum momentary workload calculated during the data run, 2) number of times in the simulation run that workload exceeded 60 (high), 3) number of times that workload exceeded 100 (very high), 4) the percentage of time spent over the high threshold, and 5) the percentage of time spent over the very high threshold. These five metrics are used in this thesis.

## C. MGV COMMON FUNCTION MODEL (CFM)

IMPRINT analysts with ARL/HRED, the FCS LSI (Boeing, SAIC) and the V.I. team (BAE and GDLS) have developed a CFM based on the CCS FA/TA discussed earlier. The CFM model is generally approved by all of the analysts involved in the project, and has been through the scrutiny of multiple SMEs to ensure it is a valid representation of the task-network and functional flow anticipated for crews in the CCS of the MGV fleet. This model, provided by analysts from BAE to the author, acts as the baseline for the task-loading analysis in this thesis.

Using the proposed scheme in Figure 13, the Local Defense function (CFM5) of the baseline was modified to reflect the new and resulting human-automation scheme by 'dialing in' selected levels of automation for selected tasks. The exact task-network changes are not reproduced here, but Figure 14 is provided to give the reader an understanding of how the Local Defense task-network in the CFM was modified to account for the proposed human-automation interaction. The full task-network model is available electronically from the author on request.

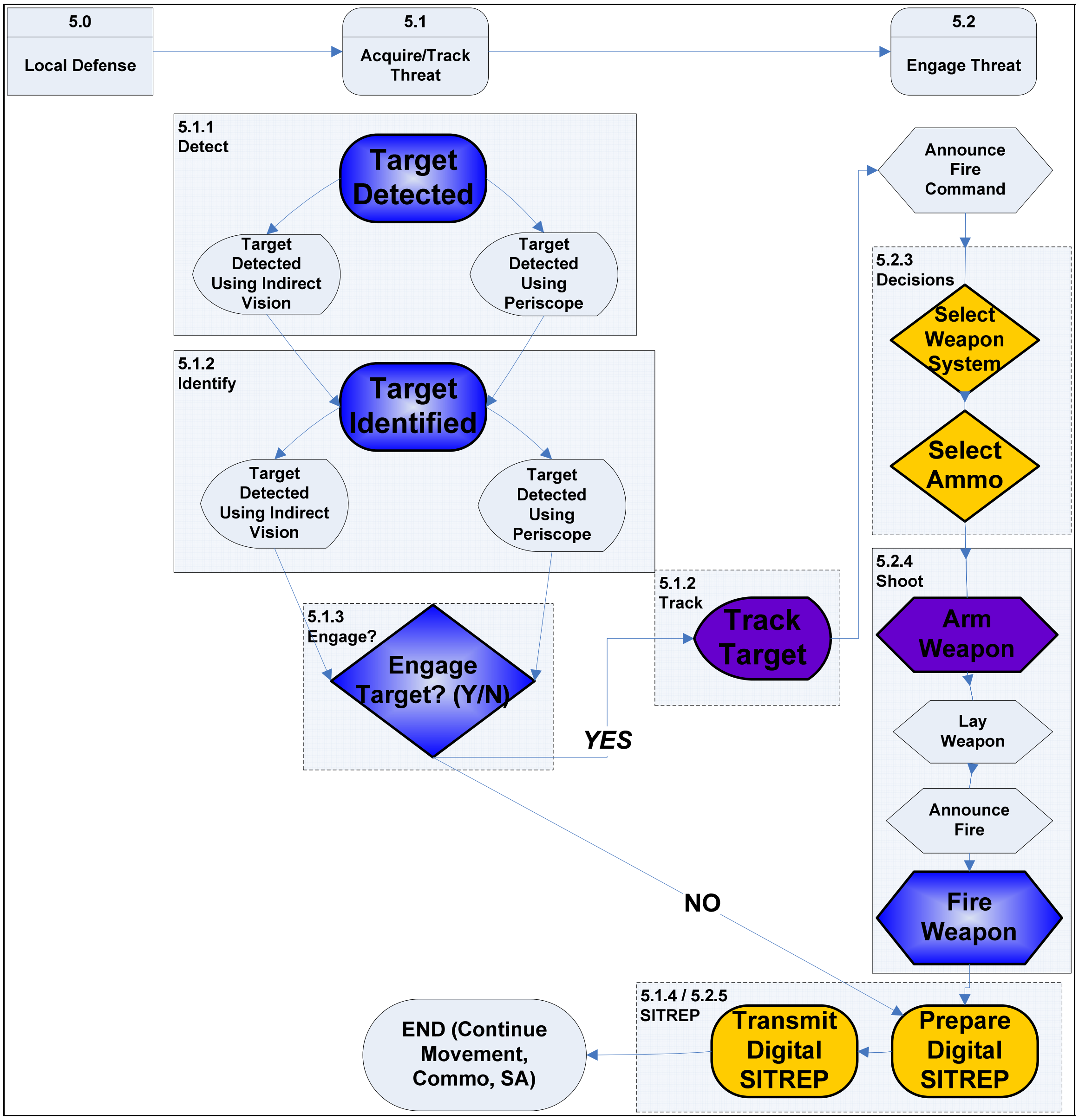


Figure 14. Local Defense (CFM Function 5.0) from Figure 12, modified to reflect the types of levels of automation applied as per Figure 13.

While IMPRINT is a great tool for early analysis, it cannot fully capture the nuances of the proposed human-automation interface in the estimates of cognitive resources, task completion times, etc. IMPRINT is limited in its ability to fully model the interaction and subsequent operator human, but its results do provide some bounds and guidance on the real problem of crew size and paired human-automation behavior in the MGV fleet.

To collect baseline data for the analysis, the simulation was run for 60 minutes. A set of random number seeds were generated in Microsoft Excel for use in the random number seed part of the simulation. After inputting the random number seed and executing the baseline CFM model, it took approximately 2-5 minutes to complete the simulation and generate the data into Excel. Then another random seed was entered and the simulation run again, continuing this process a dozen times to get a set of usable data that the author felt comfortable with.

As with the baseline CFM model, simulation was run for 60 minutes to permit side-by-side comparison of the five workload metrics. However, completing the data runs for the modified CFM was a much longer, more involved process. First attempts at modifying the CFM involved breaking each baseline tasks into two or more tasks, which were carried out by human and automation in parallel in the task network. The subtasks assigned to automation were carried out without error in no time and with no workload channel values. The subtasks assigned to the human were given modified workload channel values based on the nature of the resulting interaction with automation. This process of assigning new tasks and workload values carries as much 'art' as it does 'science'. It is entirely up to the modeler, with his experience and expertise, to guide the process. After some early data runs, the author realized the method of having the subtasks in parallel was causing unintelligible results: all of the workload results were in the many, many times in excess of the baseline CFM scores, indicating a serious problem with the veracity of the model.

Realizing this was an error, the author then shifted to running the resulting subtasks in serial. Repeated modifications of the model and about an additional 60 data runs were necessary before IMPRINT yielded intelligible results. Further modifications to the task-network eventually were necessary to capture the some of the intricacies of the proposed human-automation interaction and predicted task-loading (i.e., MWL, a key component of human performance). All told, the author completed over 250 data runs.

Once the author was comfortable with the execution of the modified CFM, the author ran another set of eleven data runs using the same random number seeds as the baseline analysis, and then tabulated the scores for five chosen metrics. In effect, using

the same random seeds simulated using the same human subjects for both the baseline and modified CFM. This is a key variance reduction technique, and allowed a side-by-side comparison of the baseline CFM versus the modified CFM.

## D. PLAN FOR QUANTITATIVE ANALYSIS

Given the baseline-modification plan of action, the plan for data analysis was straightforward. In this case, the baseline CFM and the proposed modifications represent a classic 'before-after' comparison, and the paired *t*-test is appropriate. The data for the five metrics collected above (maximum workload, number of time over 60 and 100, percent of time over 60 and 100) were compared via the paired *t*-test. The data certainly displayed interval/ratio scale properties. The assumption of normality in the paired differences was reasonable for three of the metrics, but somewhat weak for two others. Thus, the five before-after metrics were also compared via the equivalent nonparametric inferential statistic, the Wilcoxon Signed Ranks Test (WSRT). The conclusions were the same regardless of the test conducted.

# V. RESULTS OF QUANTITATIVE ANALYSIS VIA IMPRINT

Eleven data runs were conducted each for the baseline MGV CFM as well as the modified CFM with the proposed human-automation interface scheme out of Figure 11. Table 8 shows the tabulated results from the baseline CFM, while Table 9 shows the tabulated results for the modified CFM. Each simulation run was conducted eleven times with the common random number seeds. The sample mean and standard deviation are at the bottom of each table to gain an understanding of the variability in the data.

Table 8. Analysis of Baseline MGV CFM

| Run | Maximum Workload | Number of Times Workload Exceeds (>) 60 | Number of Times Workload Exceeds (>) 100 | Percent of Time Over High Threshold (> 60) | Percent of Time Over Very High Threshold (> 100) |
|---|---|---|---|---|---|
| 1 | 297.26 | 792 | 401 | 46.22% | 21.44% |
| 2 | 428.76 | 751 | 449 | 49.15% | 24.72% |
| 3 | 451.88 | 1055 | 723 | 64.58% | 39.36% |
| 4 | 589.65 | 2614 | 2254 | 85.94% | 72.65% |
| 5 | 1100.08 | 3381 | 3200 | 87.03% | 80.25% |
| 6 | 412.11 | 847 | 469 | 49.02% | 24.15% |
| 7 | 213.33 | 627 | 233 | 35.32% | 11.43% |
| 8 | 353.92 | 1222 | 820 | 67.24% | 40.75% |
| 9 | 586.23 | 926 | 588 | 52.84% | 31.63% |
| 10 | 284.02 | 581 | 232 | 34.01% | 11.68% |
| 11 | 431.67 | 812 | 514 | 49.22% | 28.48% |
| $\bar{x}$ | 468.08 | 1237 | 898 | 56.41% | 35.14% |
| $s$ | 245.70 | 941 | 981 | 18.57% | 23.26% |

Comparison of the five metrics via paired *t*-test yielded statistically significant differences in four of the five metrics (Table 9). The number of times workload exceeded 60 and 100, and the percentage of time workload was over 60 and 100, were significantly lower in the modified CFM than in the baseline CFM. The difference in maximum workload was not significant.

Table 9. Analysis Results of Proposed Human-Automation Interface Scheme Applied to MGV CFM

| Run | Maximum Workload | Number of Times Workload Exceeds (>) 60 | Number of Times Workload Exceeds (>) 100 | Percent of Time Over High Threshold (> 60) | Percent of Time Over Very High Threshold (> 100) |
|---|---|---|---|---|---|
| 1 | 270.14 | 538 | 231 | 34.06% | 11.79% |
| 2 | 382.25 | 680 | 372 | 31.02% | 13.34% |
| 3 | 675.88 | 924 | 585 | 49.16% | 28.06% |
| 4 | 444.44 | 997 | 655 | 57.60% | 38.81% |
| 5 | 808.38 | 2568 | 2311 | 85.32% | 75.89% |
| 6 | 497.86 | 1170 | 767 | 65.72% | 38.38% |
| 7 | 213.33 | 603 | 236 | 33.45% | 10.91% |
| 8 | 420.67 | 803 | 422 | 44.47% | 21.06% |
| 9 | 208.5 | 479 | 215 | 30.21% | 11.61% |
| 10 | 262.82 | 487 | 218 | 27.83% | 10.39% |
| 11 | 216.63 | 485 | 201 | 27.05% | 9.98% |
| $\bar{x}$ | 400.08 | 885 | 565 | 44.17% | 24.57% |
| $s$ | 413.08 | 920 | 598 | 45.18% | 25.84% |

Table 10. Results of Comparison by Paired *t*-test

| Metric | Mean Difference | SE Mean | *t* | *df* | *p*-value |
|---|---|---|---|---|---|
| Maximum Workload | 68.00 | 53.05 | 1.282 | 10 | .229 |
| Number of Times > 60 | 352.182 | 153.57 | 2.293 | 10 | .045 |
| Number of Times > 100 | 333.636 | 155.57 | 2.145 | 10 | .058 |
| Percent of Time > 60 | 12.24% | 3.95% | 3.102 | 10 | .011 |
| Percent of Time > 100 | 10.57% | 3.84% | 2.756 | 10 | .020 |

Since the assumption of normality in the paired differences was weak in two cases, comparison of five metrics was also conducted via the WSRT (Table 10). The conclusions are the same as the paired *t*-test results.

Table 11. Results of Comparison by Wilcoxon Signed Ranks Test

| Metric | *T* | *p*-value |
|---|---|---|
| Maximum Workload | 1.282 | .285 |
| Number of Times > 60 | 2.293 | .016 |
| Number of Times > 100 | 2.145 | .021 |
| Percent of Time > 60 | 3.102 | .016 |
| Percent of Time > 100 | 2.756 | .021 |

# VI. DISCUSSION

## A. DO NOT OVEREMPHASIZE THE STASTICAL RESULTS

The goal of this thesis was to provide a process for developing a top-down, overarching approach to explicitly define and design the interaction between proposed automation schemes and the human crew. It shows an approach to developing a functional architecture between human and automation for the total system. In effect, it constitutes the design methodology and automation philosophy, as espoused by Rouse et al. (1987). While it was developed for engineers and scientists at BAE and the V.I., the process can be expanded to a wide array of domains (aviation, space, maritime, ground transportation, manufacturing, etc.). Chapter III covered the development of the qualitative to drive the design process. It is a logical approach to function decomposition with a reasonable paradigm to use to conceptualize the shared roles between human and automation. With this tool in hand, the exact role of the Soldier operators as the central component of the vehicle systems can be more clearly understood well before the fielding of the vehicle systems.

The results show that it is possible to gain a reduction in operators task-loading, but is not inevitable. Using IMPRINT, we associate task-loading with the *construct* of mental workload, an idea that cannot be easily measured under any circumstances. The research community generally accepts MWL as a key facet of overall human performance, but simply lowering MWL will not necessarily improve human (and thus system) performance. Simply adding more automation will not automatically decrease task-loading and mental workload. The literature review in this thesis should convince the reader of these assertions.

The thesis demonstrated that the proposed model can be implemented in IMPRINT as a way to quantify the effects of the proposed human-automation interface scheme on task-loading predictions (and thus mental workload). Only the Local Defense function of the CFM was quantitatively modeled, but it helps us gain some understanding of the human performance ramifications of the proposed model, as per the primary

evaluative criteria put forth by Parasuraman et al. (2000). In this way, we can take a step towards reducing workload peaks and improving human performance.

A primary conclusion of the thesis is that by applying the proposed human-automation interface model to other functions in the vehicles, both in the CFM and in vehicle-specific function, it is possible to make further reductions in operators task-loading, and this MWL. This will also support attempts to achieve the current ORD requirement for a vehicle operable by a 2-soldier crew. This work is intended to contribute to the effort to ensure that vehicle systems in the MGV fleet can accomplish the overall unit mission and the FCS' mission as an acquisition program. Even if we eventually conclude that an additional crewmember is required on the various MGV vehicles, the same qualitative and quantitative models can be used to gain a clear understanding of the human-automation interaction as well as the some of the human performance ramifications in terms of mental workload.

Caution should be taken not to overemphasize the results of the paired comparisons in the Results. Again, the goal of the thesis was to demonstrate how the proposed interface scheme might be quantitatively modeled. There are many knowledgeable IMPRINT practitioners who can improve on the steps taken in this thesis to quantify the possible human performance ramifications. Echoing previous IMPRINT technical reports and papers (Mitchell, 20005; Mitchell et al, 2003), this type of quantitative analysis can direct the engineer and researcher towards areas of task demand in new, manned systems that need improvements.

Another key point to make about the possible reductions in task-loading (and thus, MWL) is to understand that they are possible **if, and only if** it is possible to design the automation to the levels recommended in the proposed model! If the proposed automation level is not technically feasible, or costs too much to achieve, then you may not be able to achieve the predicted operator task-loading predictions. Should engineers and designers be forced to 'dial down' the LOA for a function, modifying the IMPRINT analysis is a possible way to understand the implications on task-loading, and thus possible ramifications for human performance.

There is a final note of caution in interpreting the results. In the midst of making the 250+ data runs in IMPRINT with the different random number seeds, there were several cases of extreme outliers in terms of calculated task-load, with maximum workload scores reaching in excess of 2000 on one or two occasions. It merely goes to show that IMPRINT, while a wonderful tool for analysis of systems early in the design process, has inherent variability and that multiple runs with common random number seeds are necessary achieve accurate estimates of workload.

The author is firmly convinced that if he took the time to replicate the analysis over 40-50 data runs (with common random number seeds to reduce variability and induce the paired *t*-test), that the results would yield at least 3-5 severe outliers in terms of workload score. Post-hoc analysis of some outlier cases shows that the simulated vehicle commander was trying to accomplish unrealistic number of tasks simultaneously. In some instances, not only was the commander conducting various tasks in the Local Defense function, but the simulation might have the same person monitoring the driver, talking on the intercom, typing a digital message, and more. This artificially drives the momentary workload score into unrealistic totals. In real operations, the vehicle commander would have shed and/or prioritize tasks in order to bring his workload under some semblance of control. To paraphrase legendary Frederick Taylor, the 'father of scientific management', he would be required to have too many hands, too many feet, and too many heads (Taylor, 1957).

Post-hoc analysis of other outlier cases reveals another situation that IMPRINT analysts must be wary of. This thesis made modification to only the Local Defense part of the CFM, leaving the remaining functions unchanged. There was one case during early data runs where a certain random number seed simply never called upon the Local Defense function, even after 60 minutes of simulated action. In that case, the total workload metrics became severe outliers because the simulation never called on the functions where automation had been 'dialed in' to help the human operator! In that case, the random number seed and its results were discarded. The prudent practitioner will not make conclusions from only a single data run, but rather after at least 10 data runs to gain some idea of the variability involved the simulation.

## B. WHAT IMPRINT DOES NOT ACCOUNT FOR

The results of this thesis should not be construed as an argument that the MGV fleet can be operated with only two soldiers. Nowhere does this thesis make that argument or conclusion. While the thesis has been able to show how the application of the qualitative human-automation interaction model can bring a possible reduction in operator task-loading due to purposely designed automation features, it would be a serious (and unfounded) leap of logic to conclude that it can ensure adequate human performance by a two-soldier crew.

The CFM analysis via IMPRINT concentrates wholly on combat operations in the MGV common crew station, arguably the most intense and cognitively difficult mission segment of the MGV fleet. However, the IMPRINT models do not account for a host of other functions that the MGV fleet and its crew members will take on outside of combat operations that can be very demanding, both mentally and physically (personal communication, John Lockett, 27 September 2005). It would be careless not to point out that the models, in their present state, do not even attempt to account for activities such as crew rest (sleep), performance under fatigue, environmental taxons such as heat, cold, and/or chemical-biological warfare environment. The models do not account for physical labor required in certain resupply and logistics operations, where an extra crew member may be invaluable in loading, unloading, or cross-loading of ammunition, food, water, and other supplies. Lastly, the model, running only 60 minutes, does not attempt to understand how crews would perform and rest under long-tern operations, such as the 72-hour mission profile dictated in the FCS O&O Plan and ORD.

## C. HSI (MANPRINT) DOMAINS – IMPLICATIONS AND TRADEOFFS

The proposed human-automation interface scheme for the MGV fleet can contribute to multiple HSI (MANPRINT) domains that will require trade-off analysis to resolve. We can anticipate impacts to nearly all of the domains, including Manpower, Personnel, Training, Human Factors Engineering, System Safety, and Soldier Survivability (see US DoDI 5000.2, pp. 32-33, and US Army Regulation 602-2 for details of the HSI/MANPRINT domains and their definitions).

### 1. Manpower and Personnel

The trade-off between the crew-size requirements in the ORD and overall crew performance was the prime initiator of this thesis. Simply writing and approving a requirement for crew of set size is not enough. The crew-size requirement must be balanced with requirements in human factors engineering and overall human performance. A primary conclusion of the thesis is that by applying the proposed human-automation interface model to other functions in the vehicles, both in the CFM and in vehicle-specific function, it is possible to make further reductions in operators task-loading, and MWL. This will also support attempts to achieve the current ORD requirement for a vehicle operable by a 2-soldier crew. This work is intended to contribute to the effort to ensure that vehicle systems in the MGV fleet can accomplish the overall unit mission and the FCS' mission as an acquisition program.

However, further analysis using the Target Audience Description (TAD) may reveal that not just any soldier will be able to man a vehicle in the MGV fleet. It may prove much more difficult for a brand new soldier or lower-category soldier to efficiently and effectively operate these highly advanced crew stations across the MGV fleet. Rather, it will a soldier with more experience or more intelligence (i.e. higher test scores) to operate in the crew station with advanced automation schemes.

An additional consideration is the range of military occupational specialties (MOS; see US Army Pamphlet 611-21) that will man the CCS of different vehicles in the MGV fleet. Infantry soldiers will be in the ICV, tankers in the MCS, medics in the MV, artillery soldiers in the NLOS-Cannon, various logistics and maintenance in the FRMV, etc. Each of these MOS has unique requirements for physical strength, medical status, and intelligence/aptitude. Yet, they will all be manning a similar CCS that may not take into account the differing personnel requirements of all the MOS called to man the crew station in the O&O plan.

### 2. Training

Regardless of final design of the human-automation interaction scheme in the MGV fleet, it will be necessary to acquaint soldiers in training as to the exact nature of the resulting interaction between themselves as operators and the software/hardware automation. The extensive literature base available on human-automation performance makes it quite clear that humans and failures often occur when the operators simply do not understand what the automation is doing, best expressed when humans start asking: What is it doing now? What will it do next? Why did it do this?" (see Woods & Sarter, 1998)

As with the possible need for a higher category of soldier to man the MGV, the requisite amount of training in the CCS will likely increase. This is especially true if high levels of automation are introduced in some functions. The soldier-operators must be able to clearly understand what any automation scheme is doing 'behind the scenes', so to speak. They must have a succinct and accurate 'mental model' of the overall operation so that they are able to anticipate, troubleshoot, and even take over from the automated system when necessary. Simply believing that certain tasks and functions work 'like magic' is a recipe for human error and system failure, thus a degradation in system performance.

A final item in training is the issue of soldier trust in automation. As a crewman and part of this total vehicle system, the soldier-operator's trust in the automation is dependent on his familiarity with the automation scheme. This could demand longer training periods (in or out of the schoolhouse) and high fidelity training aids, devices, simulators, and simulations (TADSS). There are also accounts of operator misuse of automation, where excessive trust can lead operators to rely uncritically on automation without recognizing its limitations or fail to monitor the automation's behavior (Parasuraman & Riley, 1997; see also Parasuraman & Miller, 2004; Lee & See, 2004).

The increased training demands may be alleviated through well-conceived, human-centric embedded training, performance support systems, and job performance aids.

### 3. Human Factors Engineering

This thesis has largely been a human factors engineering effort, but with definitive effects on other HSI/MANPRINT domains. The proposed qualitative model has a goal of not only defining the human role in the overall system, but also in keeping MWL at an acceptable level during the entire functional flow. It fosters improved human performance as part of the total vehicle system, in turn enhancing system effectiveness and suitability. IMPRINT is a good way to quantify the effects of task-loading, and is in extensive use already in the MGV program.

### 4. System Safety and Soldier Survivability

The potential impacts of this thesis are similar for the System Safety and Soldier Survivability (SSv) domains, though probably less effect. System safety experts normally conduct extensive Failure Modes Effects Analysis (FMEA) and Failure Modes Effect Criticality Analysis (FMECA) concurrently as a system moves from Milestone B towards Milestone C in the DoD systems acquisition process. The FMEA/FMECA efforts should be widened slightly to look at the interaction between hardware/software automation and the soldier-operators. Ignoring the interaction causes the FMEA/FMECA efforts to miss possible key points of system failure that may not be attributable directly to software, hardware, or human.

The impact on SSv, similar to FMEA/FMECA, lies along the analysis of potential fratricide as a result of a breakdown or misinterpretation of the human-automation interaction scheme in the vehicles. Recommended automation levels allow sensors and software (automation) to be much more involved in the acquisition, analysis of target information than in the past, targets that may be friendly. Likewise, automation in the form of decision/action support may err and recommend action against a friendly target based on automated target assessment. SSv assessments using the US Army Research Lab's PAL (Parameter Assessment List) should include checks on any possible fratricide potential caused by unexpected (or incorrect) human-automation interaction.

## D. FURTHER ACTIONS

Parasuraman et al. (2000) proposed both primary and secondary evaluative criteria that provide a good road map of further actions as the design of the MGV crew stations continue. In the primary evaluative criteria, this thesis was wholly focused on the MWL aspect, analytically predicting task-loading as a result of the crew station and it proposed human-automation interaction. Once simulations and prototypes are available for user demonstrations, it will prove useful to empirically evaluate mental workload via a variety of means (physiological, primary task, secondary tasks, or subjective rankings; see Gawron, 2000), and then look at the relationship between MWL and actual crew performance.

Parasuraman et al. (2000) emphasize the importance of testing and evaluating preliminary choices of automation functionality. Iterative testing against the proposed primary and secondary evaluative criteria will establish the best automation levels for the system. Complacency, skill degradation, and the constructs of SA can be evaluated throughout the development testing and operational testing (DT/OT) schedules. Additionally, the proposed models in this thesis and the MGV crew stations are natural candidates for rapid prototyping and experimentation (see Moore, Kennedy, and Kern 2003; Kennedy and Durbin, 2005 for examples). Use of these tools and techniques during the system design and development phase of the DoD acquisition process can be the primary ways to gather data on human performance (primary evaluative criteria).

Finally, the entire FCS program is decisively moving from concept to reality. Further iterations of the systems engineering process will continue to further define and refine necessary the details of the MGV crew stations and the exact roles for soldiers as the operators and maintainers. Human factors engineers, manpower and personnel specialists, training designers, and safety, health and survivability analysts will be needed to round out a design team with other engineers of various backgrounds (software, electronics, mechanics, etc.). User groups and SMEs will also be necessary to evaluate and refine the design as the system takes form.

# VII. CONCLUSIONS AND RECOMMENDATIONS

This thesis provides human factors engineers, systems engineers, designers, and developers a top-down, overarching approach that enables them to explicitly define and design the interaction between proposed automation schemes and the human crew. In effect, it constitutes the design methodology and automation philosophy, as espoused by Rouse et al. (1987). A qualitative model was proposed to drive the functional architecture and human-automation interface scheme on the Army's FCS manned vehicle fleet. The proposed model is applied to a portion of the functional flow of the MGV common crew station It is a logical approach to function decomposition with a reasonable paradigm to use to conceptualizing the shared roles between human and automation. With this tool in hand, the exact role of the Soldier operators as the central component of the vehicle systems can be more clearly understood before the fielding of the vehicle systems. The proposed model was then demonstrated quantitatively via a computational task-network modeling program (IMPRINT), to gain an understanding of the impacts on human task-loading, and therefore workload and human performance.

Judicious application of the proposed qualitative model, coupled with quantitative analysis of the task-loading effects via IMPRINT, can be continued for other functions in the various MGV crew stations. This will further provide a guide to defining the relationship between human and automation and the resulting human performance ramifications. This is but *one way* (among several) to work toward the ORD requirement for a 2-soldier crew. But, even if the 2-soldier crew requirement is relaxed, a coherent plan for automation will help to ensure soldier performance and system effectiveness. The focus of the model is to ensure that a reduced-crew can perform *well enough* (not optimally) to accomplish all of the functions and tasks asked of the total vehicle system. If we eventually conclude that an additional crewmember is required on the various MGV vehicles, the same qualitative and quantitative models can be used to gain a clear understanding of the human-automation interaction as well as the some of the human performance ramifications in terms of mental workload.

While this thesis focuses on ways to solve real technical issues in the FCS MGV fleet, the model and analytical processes proposed, or similar approaches, certainly are necessary in a wide array of complex systems in multiple domains (aviation, space, maritime, ground transportation, manufacturing, etc.). As a thorough literature review reveals, there are very few people thinking about an 'automation philosophy' to guide the complex interactions between humans and automation to ensure total system performance. So while the proposals here were developed for the FCS MGV fleet, they are in no way limited to that particular application.

# APPENDIX. ADDITIONAL EXAMPLE OF THE MODEL IN ACTION – US NAVY'S LITTORAL COMBAT SHIP

Included is the complete paper titled *Developing a Human-Automation Interface Model of the Littoral Combat Ship's Fire Control System*. It was published in the proceedings of the 2005 Human Systems Integration Symposium held 20-22 June 2005 in Arlington, VA.

**Joshua S. Kennedy, Jeffrey A. Thomas, and John M. Green**

# Developing a Human-Automation Interface Model of the Littoral Combat Ship's Fire Control System

## ABSTRACT

This paper outlines how Human Systems Integration (HSI) methodology was used to design a fire control system for the U.S. Navy Littoral Combat Ship (LCS) as an example, with an emphasis on reductions in manning. The design team's original objective was to design a control system for the main gun that could be operated by one person or less. Mission analysis of the LCS and its weapons systems generated possibilities for manning reduction that extend well beyond the ship's main gun. The team's application of HSI methodology gave rise to a 'fire control system' where the operator-automation team could accomplish the ship's surface warfare as well as air self-defense missions with only one sailor. The team applied a model of human interaction-with-automation to outline the design methodology (Parasuraman, Sheridan, & Wickens, 2000). This approach also delineates several tradeoffs among HSI domains to be made in further iterations of the HSI process. In order to ensure optimal system performance, it is critical to implement HSI methodology for all complex systems requiring a human interface.

## INTRODUCTION

In support of its Sea Power 21 strategic vision, the U.S. Navy is developing the Littoral Combat Ship (LCS) to deliver focused mission capabilities to enable joint and combined forces the capability of defeating the conventional and asymmetric access-denial threat in the littoral area (U.S. Navy PEO Ships, 2004).

The littoral area of control extends from the open ocean, to the shore, and to those inland areas that can be attacked, supported and defended directly from the sea. The LCS will defeat enemy littoral defenses including mines, fast swarming small boats, and submarines, ultimately ensuring maritime access in any environment (see figure 1). "Working together as part of a netted distributed force, this future fleet will project power forward and enable naval and joint task force commanders to dominate the littoral battlespace" (US Navy, 2004).

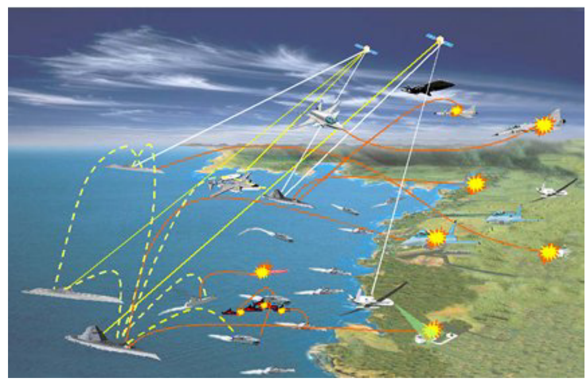

**Figure 1 Artist Conception of Littoral Battlespace**

### Mission Analysis

This project was a course requirement for SI4001 (Systems Integration and Architecture) as part of the new HSI Masters of Applied Science program at the Naval Postgraduate School (NPS), CA. The professor is the third author. In the beginning of the course, he issued this directive: "Design a control system for the LCS guns that can be operated by one person or less". Our team understood this to be a primitive need statement that supports minimal manning and provided a starting point for the analysis process.

At first glance, we were tempted to use the traditional approach of applying only human factors engineering design concepts to design

a computer display for the LCS gun system. However, since it is closely related to systems engineering (SE), the HSI process must begin with a thorough understanding of the U.S. Department of Defense and the U.S. Navy's needed capabilities (requirements analysis). Three Navy lieutenants and four Army civilians conducted background research into the LCS and various gun systems to identify capability gaps between legacy gun systems and the intended capabilities of the LCS gun system. We derived an accepted gun system designed from the user's perspective to enable and enhance the LCS capabilities in the littoral.

The LCS Flight 0 Interim Requirements Document (IRD) was the primary reference document (US Navy 2003). The LCS focused mission capabilities are mine warfare (MIW), littoral surface warfare (SUW) against small, highly armed boats, and littoral anti-submarine warfare (ASW). Its inherent mission capabilities include joint littoral mobility, maritime interdiction/interception operations, homeland defense, and others. In addition, to support its focused and inherent mission area, it must also have core capabilities for air self defense (ASD), survivability, aviation support, logistics, and others. Based on the IRD, the gun control system for the LCS must help enable the LCS to achieve these capabilities—and do it with one operator or less.

## Going from a "Gun Control System" to a "Fire Control System"

Mission analysis of the LCS and its weapons systems generated possibilities for manning reduction that extended well beyond the ship's main gun. The team's application of HSI methodology gave rise to a 'fire control system' where the operator-automation team could accomplish the ship's surface warfare as well as air self-defense missions with only one sailor. The system is made up of not only the hardware and software, but also the humans that must operate, maintain, and support it. The human element of the system will ultimately affect its operational effectiveness and suitability.

After gaining an understanding of the LCS missions and what the gun control system must support, we began to ask some questions:

Q1) What exactly are the targets of the gun system?
A1) The naval officers on the team said it would be the surface threat of multiple small boats.
Q2) Will the gun system ever shoot at an aerial threat, like a threat aircraft or an anti-ship cruise missile (ASCM) as per the ASD capability?
A2) No. Other systems on the LCS address the aerial threat. For example, the MK 15 Phalanx Close-In Weapons System (CIWS) can be used against ASCM, the SM-2 Standard Missile SM-2 can be used against threat aircraft, and the RIM-7 Sea Sparrow missile against either.

Q3) Will the CIWS, SM-2, or RIM-7 ever be used against surface threats?
A3) No, they are strictly for ASD.

Q4) What does the gun system do during MIW and ASW?
A4) Nothing, there are other weapons systems used for those missions.

So then we asked ourselves the crucial question: *Can we have one operator control the weapons for both SUW and ASD?* At this point in the process, we hatched the idea to band together these mission capabilities under a single operator. Of course, this concept is easier conceived than realized, so the rest of this paper portrays our application of HSI methodologies while working on this idea.

Consequently, our proposal is more than a gun system—it is an integration of the SUW and ASD weapons systems into a fire control system (FCS) that can be run by one sailor. This FCS will integrate the gun system to support the SUW focused mission capability, plus any combination of CIWS, SM-2 and

RIM7 to help achieve the ASD capability (both ASCM and threat aircraft. Figure 2 shows a graphic representation of our proposal.

The mission statement of this fire control system will be to enable the LCS to effectively deliver primary and inherent mission capabilities in the littoral. It shall be operated by one person or less. It shall integrate and use the common tactical picture (CTP) to detect, track, engage, and destroy targets. Its primary objective will be to conduct SUW and ASD independently or as part of a carrier strike group (CSG) or expeditionary strike group (ESG).

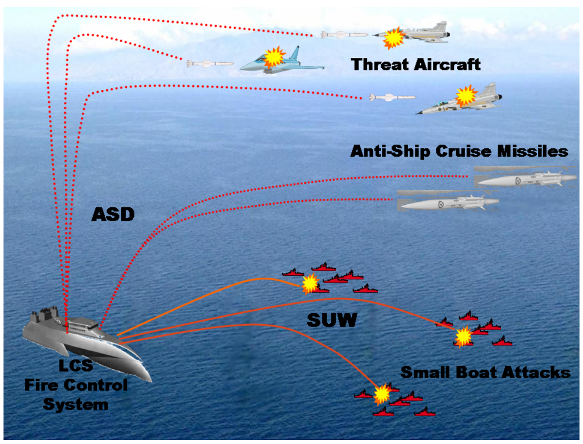


**Figure 2. Proposed Fire Control System**

## Assumptions

To begin setting up a functional flow for the FCS and its automation, we had to make several assumptions. First, any control system on the LCS will be based on the threat posture of the ship, typically determined by the ship's commanding officer or higher authority. To begin the design, we designated three postures similar to (in order of severity): WHITE, YELLOW, and RED. The color codes are also used as air defense warnings by the U.S. Department of Defense (DoD) to denote degree of air raid probability. In our system, WHITE means attack by hostile forces is improbable, YELLOW means attack by hostile forces is probable, and RED means attack by hostile forces is imminent or is in progress. This threat posture will determine the level of FCS automation in use, and represents the first time a human interfaces with the overall system.

As a necessity to begin the functional flow, we also assumed high trust, due to reliable automation. This assumption will be rigorously evaluated during its life cycle, but further design is very difficult without it.

Lastly, we assume that a high threat environment equals a high mental workload environment. If there are multiple surface and aerial targets to detect, track, identify, and engage, then the operator's mental workload (MWL) will be appreciably higher. The ship will likely be at threat posture RED. Conversely, a low threat environment equals a low mental workload environment (i.e. threat posture WHITE).

## Functional Flow

As shown in figure 3, the FCS functional flow has six major functions that are iteratively performed for each new contact:

1. Search for contacts
2. Detect
3. Track
4. Classify
5. Resolve
6. Shoot

Most of these functions are self-explanatory, but two of them need further definition. Step 4, Classify, is where the FCS determines if the target is a threat or not. Since the FCS is made up of hardware, software, and humans, this function may be carried out by any combination of these components, depending on the automation design. Step 5, Resolve, has a dual meaning. In this stage, the system seeks to gain greater *resolution* on the target, acquiring more information to help decide whether to attack it or not. This stage is also about *resolving* to destroy or not. Classify and Resolve are functions where the system will

have to make multiple decisions prior to carrying out an action (Step 6, Shoot).

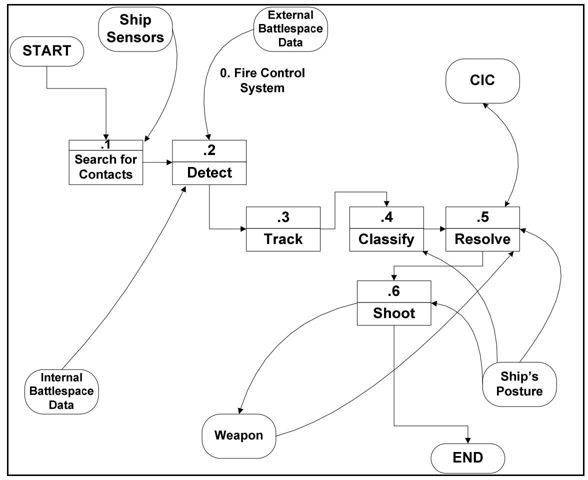


**Figure 3. FCS Functional Flow (Level 1)**

Figures 4 and 5 show a more detailed functional flow, with multiple subfunctions under the six primary functions.

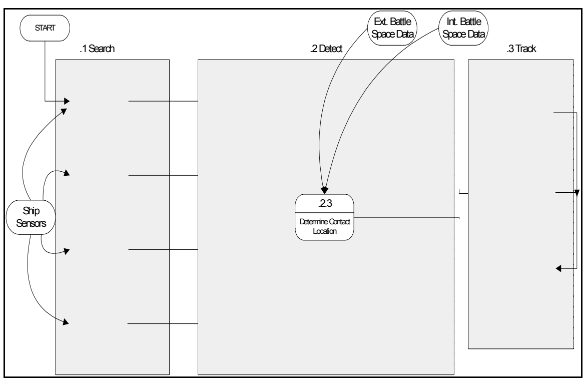


**Figure 4. FCS Functional Flow (Level 2)**

## HUMAN-IN-THE-LOOP

We have mentioned the FCS' automation several times, and that this automation must allow one operator to control weapons to support both the SUW and ASD missions. The critical question to be answered at this point is **where** and ***how*** the *operator* will interface with the automation in the functional flow of this system?

To answer this question, we needed an operator-in-the-loop paradigm.

We found such a paradigm in Parasuraman, Sheridan, and Wickens (2000), whose model is the foundation of our automation design process. Their model, for types and levels of automation, provides a framework for deciding what aspects of the system should be automated and to what extent. Appropriate selection of automation levels is important because "automation does not merely supplant but changes human activity and can impose new coordination demands on the human operator" (2000). Automation can vary across a continuum of levels, from the lowest level of fully manual control to the highest level of full automation. Table 1 shows a proposed 10-point scale, with higher levels representing increased autonomy of computer over human action (2000). For example, at a low level 2, several options are provided to the human, but the system has no further say in which decision is chosen. At level 6, the system automation gives the human only a limited time to override before carrying out the decision.

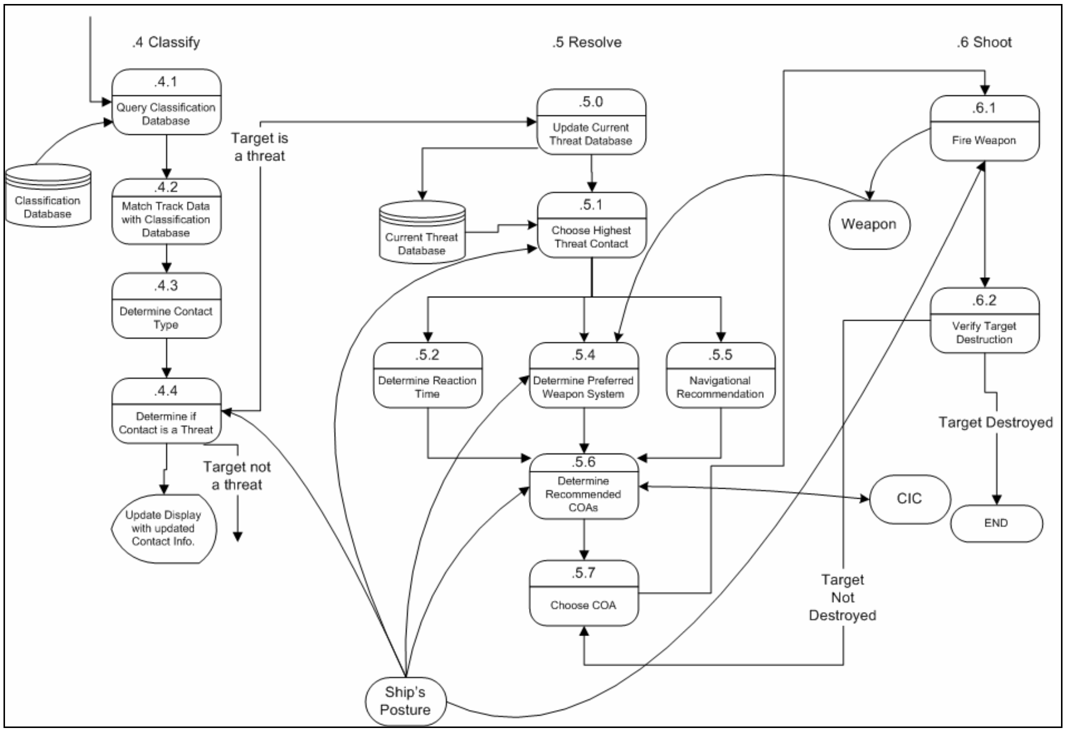


**Figure 5. FCS Functional Flow (Level 2) (continued)**

**Table 1. Levels of Automation of Decision and Action Selection (Parasuraman et al, 2000)**

HIGH 10. The computer decides everything, acts autonomously, ignoring the human
9. Informs the human only if it, the computer, decides to
8. Informs the human only if asked
7. Executes automatically, then necessarily informs the human
6. Allows the human a restricted time to veto before automatic execution
5. Executes the suggestion if the human approves
4. Suggests one alternative
3. Narrows the selection down to a few
2. The computer offers a complete set of decision/action alternatives
LOW 1. The computer offers no assistance; human must take all decisions and actions

Parasuraman et al (2000) proposed that automation can be applied to four broad classes of functions as shown in Figure 6.

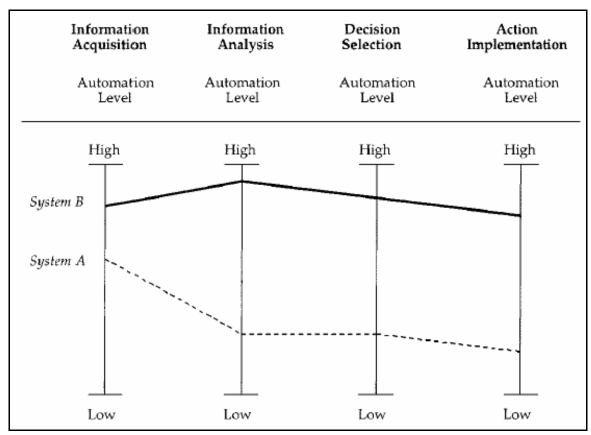


**Figure 6. Levels of Automation for independent functions of information acquisition, information analysis, decision selection, and action implementation. Examples of systems with different levels of automation across functional dimensions are also shown (Pararsuraman et al, 2000)**

Using their model, we developed an automation scheme for the FCS. In Figure 7, instead of presenting system alternatives for

analysis, we propose three possible levels of automation based on the LCS' threat posture (RED, YELLOW, or WHITE). As per our main assumption, a higher threat level (RED) means a higher level of human MWL, so we propose a higher level of automation across the four broad classes. Conversely, a low threat level (WHITE) means a lower level of MWL. In the first two stages (Acquisition and Analysis), there are high levels of automation in all three postures. The human operator is largely a supervisor in the Acquisition stage, presented with information only: the status of SUW and ASD weapons, status of various LCS sensors (radar, sonar, etc.), and status of the common tactical picture with other ships, vehicles, and aerial/space platforms, among other options.  Likewise, in the Analysis stage the automation presents the operator information about targets detected, including characteristics of the target (bearing, speed, altitude) and the symbology assigned by the FCS.

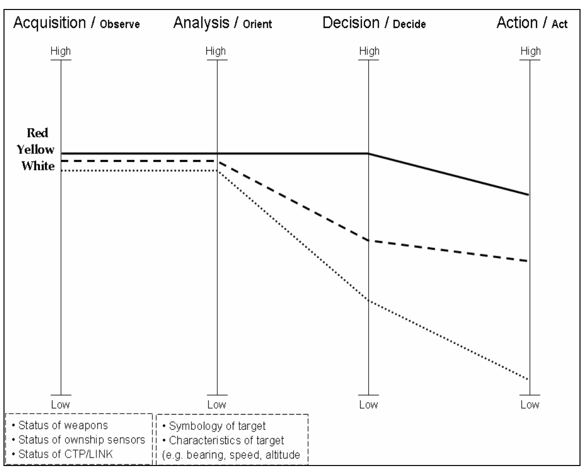


**Figure 7. First stage automation scheme for FCS.**

The human operator takes a more active role between the Analysis and Decision stages as defined by the ship's threat posture, which in turn defines the level of automation in use. In the WHITE posture, the human might have more authority over FCS decisions to be made and total control over the action to be taken. In the RED posture (high threat, high MWL), the automation might have more autonomy and the human would presumably only have authority to override the action the FCS is about to take. The YELLOW posture might take a level of automation between WHITE and RED.

We also note that the four broad functions of Parasuraman et al. are analogous to the Observe-Orient-Decide-Act (OODA) loop commonly used by DoD personnel across all U.S. military Services.

Next, we applied our functional flow to the proposed automation scheme, replacing the four broad functions with the six major FCS functions (see figure 8). Search replaces Acquisition; Detect and Track replaces Analysis; Classify and Resolve replaces Decision, and Shoot replaces Action. Again, the three possible levels of automation are RED, YELLOW, and WHITE.  For the Search, Detect, and Track functions, we reasoned that a high level of automation is warranted. The FCS, using the ship's sensor and the CTP, will search, detect and track all targets, then present real-time and concise information to the operator about those targets, as well as the status of SUW and ASD weapons, sensors, and common tactical picture.

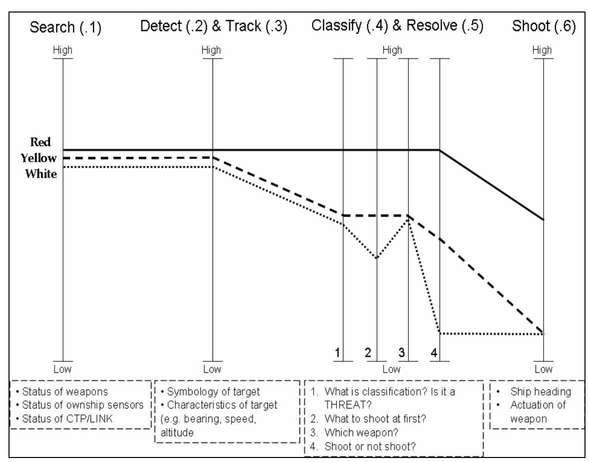


**Figure 8. Proposed Automation Scheme for the LCS Fire Control System**

The Classify and Resolve functions (replacing Decision) is present four major decisions that the system (both software and/or human operator) must make.

1. What is the classification of the target? Is it a threat?
2. What is the priority target? What should the FCS shoot at first?
3. Which weapon to use against that target?
4. Shoot or not shoot?

One major value of this automation proposal based on the Parasuraman et al. model is that system designers can fine-tune the levels of automation at each of the vertical lines in the diagram. You can simply modify the level of automation as you might move the slider bars up and down much in the same way of slider bars on a stereo equalizer, thereby achieving the balance between human and software that the system designers and engineers desire.

In the WHITE posture, due to the assumed low threat level and low operator MWL, we propose that the operator interacts more fully with the software. In the first decision, the FCS automation classifies the target and makes a recommendation to the operator, who can then confirm the classification or countermand the recommendation. This would be similar to level 4 or 5 in table 1. Continuing through the functional flow, the automation may then present a single recommendation for the highest priority target (level 3 or 4). When choosing the appropriate weapon system, automation level rises back up to level 4/5 (makes recommendation, then executes if operator approves). Since the optimal weapon to use against the selected target is entirely a function of target characteristics (surface vs. air, then ASCM vs. aircraft), we believe the automation would make a better and faster decision recommendation than the human. The final decision, to shoot or not, is left entirely to the human; the automation offers no assistance. In this regard, at the WHITE posture, the human operator will be under absolutely no pressure or suggestions to 'pull the trigger'—he will be able to make that decision unfettered by any recommendations from the software. Lastly, the actual act of actuating the chosen weapon is left entirely to the operator (who at this point is probably under supervision from a more senior officer) with no input from the FCS automation.

In the YELLOW posture, in response to the higher threat level, we can simply move up the slider bars on selected decisions to allow the system to achieve more efficient performance while probably allowing an intermediate level of operator MWL. Decisions 1-3 might remain at level 4/5, but the automation will be allowed greater autonomy (and thus influence) in Decision 4 by actually recommending to shoot at (or not shoot at) the target with the selected weapon system. However, as with the WHITE posture, the final action is left entirely to the operator (and possibly his higher supervisors).

In the RED posture, due to the assumed high threat level and to help alleviate the likely high MWL of the operator, we propose that the software maintain a higher degree of autonomy throughout the Classify and Resolve functions, probably similar to level 7 as per table 1 (software decides automatically, then informs the human; human can step and override the automation). Unlike the other two threat levels, we propose that in RED, the automation has much greater autonomy, being allowed to execute the action unless the operator overrides the action. This kind of autonomy may likely well be warranted in high threat environment with multiple surface and air threats. In addition, but noted in figure 8, is the possibility of having the FCS makes a steering recommendation for the ship, or even steer the ship itself (though this possibility may be controversial). This kind of design decision would have to be decided at the highest levels of the LCS program leadership with input from users and subject matter experts.

| Decision | Red | Yellow | White |
|---|---|---|---|
| Threat? | FCS decides, Operator must override | FCS recommends, Operator confirms | FCS recommends, Operator confirms |
| Priority? | FCS decides, Operator must override | FCS recommends one target, Operator confirms | FCS gives range of choices, Operator decides |
| Weapon? | FCS decides, Operator must override | FCS recommends, Operator confirms | FCS recommends, Operator confirms |
| Shoot? | FCS decides, Operator must override | FCS recommends, Operator confirms | Operator decides, no input from FCS |
| Action-Shoot | FCS shoots, Operator must override | Operator shoots | Operator shoots |

**Table 2. Operator-Automation Interaction at Key Decision Points**

Table 2 summarizes the proposed levels of automation for each function and the major decision points. Again, these levels are proposals based on team discussions with several subject matter experts (SMEs). The value of the Parasuraman et al. model is that further discussions within various working groups (WG) and integrated products teams (IPT), based on experience or other empirical research, can easily fine-tune the automation levels as necessary. Of course, there is also the possibility of adding or removing functions or decisions from the functional flow and subsequently the automation scheme as depicted in figure 8.

In figures 9-11, we present the latter half our FCS functional flow (figure 5) for each of the three threat postures. The four major decisions in the Classify and Resolve functions (denoted by stars) have generally increasing levels of automation as threat posture goes from WHITE, YELLOW, and then RED in response to the operational and intelligence situation. The former half of the functional flow is not presented since we proposed that automation levels remain the same in the Search, Detect, and Track functions for each of the three threat postures.

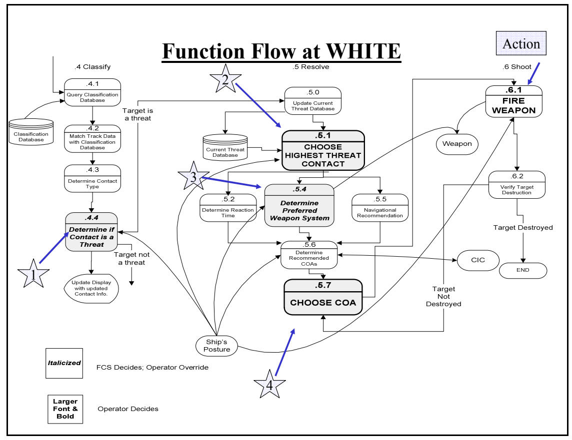


**Figure 9. FCS Functional Flow at threat posture WHITE. The four key decisions (stars) and the action are spotlighted.**

# HSI DOMAINS—IMPLICATIONS AND TRADEOFFS

The proposed FCS and its automation scheme has major impacts on multiple HSI domains, and we have identified a number of tradeoffs that need resolving should the system continue design and development.

**Manpower, Personnel, and Training (MPT)**
The zero-based manning concept drove this design from the beginning, and if the FCS concept is brought to fruition, we stand to merge manpower from three or four different weapon systems into one fire control system operator

In addition, though not discussed in this paper, there is the possibility of incorporating certain electronic warfare (EW) into the automation scheme under the same operator. Of course, all this assumes well-designed and reliable automation.

As a tradeoff for the possible manpower savings, this automation scheme will require increased development cost and time from systems software engineering. Most

acquisition officials would probably characterize it as a high-risk effort in terms program cost, performance, and schedule.

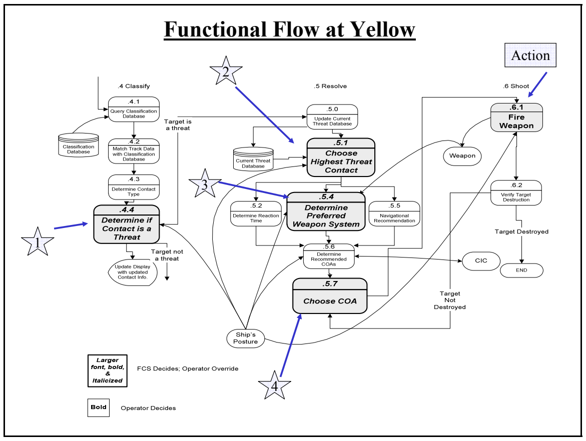


**Figure 10. FCS Functional Flow at Threat Posture YELLOW. Levels of automation of slightly higher for Decisions 1-3**

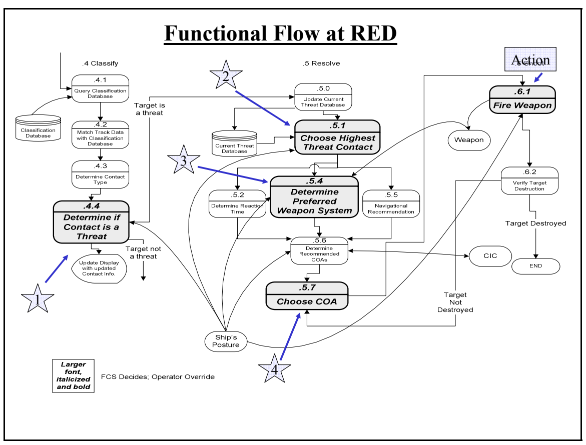


**Figure 11. FCS Functional Flow at Threat Posture RED. Level of Automation higher for All Decisions and the Action**

An additional tradeoff will be in the Personnel domain, as the knowledge, skills and abilities needed to operate this system may require higher aptitudes than current or legacy technology. It may not be possible for new sailor or lower-category sailor to operate this system; rather, it may take an experienced and intelligent petty officer or junior officer to operate the FCS as proposed.

Likewise, the requisite amount of training to operate this proposed FCS will increase. As part of this system, the operator's trust in the proposed FCS automation is highly dependent upon his familiarity with the automation scheme driving the FCS. This will demand longer training periods and high fidelity training aid, devices, simulators, and simulations (TADSS). It also points out the probable need, based on training needs analysis, for a stand-along TADSS off-ship, as well as onboard scenarios built into the FCS. However, the increased training demand may be alleviated through well-conceived embedded training, performance support systems, and job performance aids.

### Human Factors Engineering

We have an implicit goal of keeping operator MWL at an acceptable level during the entire functional flow across all possible threat postures. This is to foster improved human performance as part of the system, in turn improving overall system effectiveness and suitability. HSI practitioners can build a comprehensive workload model to assess whether MWL is kept at reasonable levels throughout the functional flow at different threat levels. For example, the Improved Performance Research Integration Tool (IMPRINT) from the US Army Research Lab (ARL) is a well-documented and widely-used tool, particularly for human performance in military applications (see the IMPRINT website at: http://www.arl.army.mil/ ARL-Directorates/HRED/imb/imprint/ Imprint7.htm.

## FURTHER ACTIONS

### Evaluative Criteria

Automation is not an all-or-none affair; rather, it can vary by type. In the Parasuraman et al. model, and as used by our team, human interaction with automation can be applied to any or all of a system's functional flow at the level required to gain

optimal system performance. Parasuraman et al. (2000) argue that

> any particular level of automation should be evaluated by examining its associated human performance consequences. These constitute the primary evaluative criteria for levels of automation. However, human performance criteria is not the only important factor. Secondary evaluative criteria include automation reliability and the costs of decision/action consequences.

Automation can have both beneficial and negative effects on human performance. There are four human performance areas that should be included in the primary evaluate criteria of this FCS: mental workload, situation awareness, complacency, and skill degradation (2000). Evidence suggests that well-designed information automation can change MWL to a level that is appropriate for the systems tasks being performed. However, "clumsy" automation can lead to increasing workload. As mentioned above in the HFE implications, MWL can be modeled during system design to assess if it is reasonable throughout system functional flow.

Besides unbalanced MWL, automation can incur human performance costs in the other three criteria suggested. Situation awareness can be negatively affected when the operators loses "awareness of the system and certain dynamic features of the work environment" (2000). If the FCS automation is highly but not perfectly reliable in executing the major decision choices, "then the operators may not monitor the automation and its information sources and hence fail to detect the occasional times when then automation fails" (2000) or is wrong. Complacency is greatest in high MWL setting when the operator is engaged in multiple tasks. Third, skill degradation can certainly occur over time if the system decisions are routinely carried out by the automation. "These potential costs—reduced situation awareness, complacency, and skill degradation—collectively demonstrate that high-level automation can lead to operators exhibiting out-of-the-loop unfamiliarity. All three sources of vulnerability may pose a threat to safety in the system failure" (2000). The FCS automation design must demonstrate that potential human performance costs, along with unbalanced MWL, do not occur. "By considering these human performance consequences, the relative merits of a specific level of automation can be determined" (2000).

Secondary evaluative criteria can include automation reliability and the cost of decision and action outcomes. Reliability is typically defined in probabilistic terms, such as a reliability of .997 or a mean time to failure of 10,000 hours. In addition, "failures may occur not because of a predictable (in a statistical sense) malfunction in software or hardware, but because the assumptions that are modeled in the automation by the designer are not met in a given operational situation" (2000). The reliability of automation also influences human trust, possibly undermining potential system performance benefits when the automation is underused or disabled. In addition to reliability, "assessing the appropriate level of automation for decisions requires additional consideration of the costs associated with decision and action outcomes" (2000).

**Incorporating Prior Research, Rapid Prototyping and Experimentation**

Our decisions on the type and level of automation throughout our functional flow was determined by team discussions, input from locally available SMEs, and our own reasoning, all with the goal of improved human performance in the resulting system (primary evaluative criteria). Additionally, there is the possibility of incorporating prior research into these decisions on the appropriate type and level. For example, prior research may have shown that compared to manual operations, both human and system

performance are enhanced by level 4 automation but degraded by automation above level 6 (2000). Based on this research, we apply the finding at the appropriate place in the framework. In lieu of prior research, performance modeling may provide similar guidelines.

Parasuraman et al. (2000) emphasize the importance of testing and evaluating preliminary choices of automation functionality. Iterative testing against the proposed primary and secondary evaluative criteria will establish the best automation levels for the system. Additionally, the proposed FCS and it automation is a natural candidate for rapid prototyping and experimentation (see Moore, Kennedy, and Kern 2003; Kennedy and Durbin, 2005 for examples). Use of these tools and techniques during the system design and development phase of the DoD acquisition process can be the primary ways to gather data on human performance (primary evaluative criteria).

Finally, the proposed FCS is still very much a concept. Further iterations of the SE process will be required to further define and refine necessary capabilities and operational requirements as part of the LCS. Human factors engineers and MPT specialists will be needed to round out a design team with other engineers of various backgrounds (software, electronics, etc.). User groups and SMEs will also be necessary to evaluated and refine the design as the system takes shape.

## CONCLUSION

The LCS is designed to fight and win the world's littoral area, but it must do so with significantly less manning than historically used on our ships. The zero-based manning concept and the constraint of a single operator likely requires the increased use of automation. Automation design is both art and science, and can be guided by the model presented by Parasuraman et al. Given the primitive need, our team judiciously applied and modified the model in order to design an FCS with an automation scheme that allows one operator to control the weapons systems for both the SUW and ASD mission of the LCS. Judicious application of the Parasuraman et al. model in other programs may help achieve reduced manning without sacrificing human and system performance.

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